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14. ABSTRACT
This project aims to demonstrate the feasibility of miniature, inexpensive, in vivo robots to provide basic diagnosis and triage in military environments. The first phase of our work will focus on the design and construction of an in vivo camera robot. The robot will be fully inserted into the patient and controlled by a surgeon at a remote location. The robot will return live video images from inside the patient to allow the surgeon to explore, diagnose, and stabilize the patient. Several functional prototypes capable of tissue manipulation, abdominal exploration, and surgical utilization have been developed. This revolutionary, robotic technology has demonstrated its applicability in natural orifice and single incision minimally invasive surgical procedures. Such innovative procedures are virtually impossible to perform without the design and creation of new tools like our miniature robots. Successful completion of prototype development is a critical first step toward our ultimate objective, development of a group of in vivo robots that can provide diagnosis and therapeutics, as it builds on previous successes and focuses on developing an image-guided robot capable of provisions of basic triage in forward environments.

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Robotic telesurgery, in vivo robot, triage in forward environment, remote first responder, laparoscopic surgery

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Introduction

This project aims to demonstrate the feasibility of miniature, inexpensive, in vivo robots to provide basic diagnosis and triage in military environments. The work is the first phase of a two phase project. The first phase will focus on the design and construction of an in vivo camera robot. The robot will be fully inserted into the patient and controlled by a surgeon at a remote location. The robot will return live video images from inside the patient to allow the surgeon to explore, diagnose, and stabilize the patient. The second phase of this project will focus on continued animal trials as well as human testing and regulatory approval. Our long term objective is to create a group of in vivo robots that can provide diagnosis and therapeutics at all echelons of military medical care.

Body

Task 1: Development of a small in vivo vision system

Planar manipulator robots, shown in Figure 1 of [1], have been built that can be inserted into the peritoneal cavity through the lumen of the intestinal tract using the upper approach. Once fully inserted, these robots can be used within the peritoneal cavity without the constraints of an externally actuated endoscopic device. The basic design of each robot consists of a central "body," with a stereo camera pair, and two "arms," with configurations for insertion and articulation. Each arm is composed of an upper arm and a lower arm, with the lower arm rotating and extending with respect to the upper arm.

Benchtop testing has demonstrated each robot's ability to successfully complete a simulated stretch and dissect task using video provided from on-board robot cameras. These robots have also been used in non-survival animal model studies demonstrating the feasibility of performing a NOTES cholecystectomy from essentially a laparoscopic platform [2]. Although these studies successfully demonstrated the feasibility of performing an in vivo robot-assisted NOTES cholecystectomy, problems were encountered. The second study was converted to an open procedure after dissection of the cystic duct due to insufficient magnetic coupling for attaching the robot to the interior abdominal wall. The third study ended prematurely due to mechanical failure of the shoulder joint. These issues have been addressed in continuing iterations of the robot design without limiting robot functionality [2]. Ongoing work with these robots includes developing software for adjusting image parameters including glare reduction and image calibration. A visual tracking system using the stereo camera pair is also being developed.

A prototype robot shoulder joint that incorporates full mobility (two degrees of freedom) while increasing both speed and end effector force is also being developed. Preliminary work included bench top testing using a shoulder test jig to develop an independent PID controller for the robot. In this control scheme the robotic arm tracks the position of the joystick as if the arm and joystick were connected and rotating about the shoulder joint of the robot.

A next generation one-armed robotic manipulator that incorporates the full mobility shoulder joint with a prismatic "elbow" joint has been built. This robot uses the same control scheme described for the prototype shoulder joint. An additional shoulder and elbow joint will be incorporated into this prototype to give a two-armed dexterous robot the same degrees of freedom as two standard laparoscopic tools working through trocars. The primary challenge with the design of a full mobility robot is meeting the competing design constraints of speed, size, and force. For these prototypes, the speed and force constraints will be met at the expense of size.

A modular wireless mobile platform for in vivo sensing and manipulation applications was developed [3]. Both ex vivo and in vivo tests of these robots with biopsy grasper, staple/clamp, video, and physiological sensor payloads were demonstrated. These tests successfully demonstrated the ability to sample tissue, manipulate abdominal organs, and provide visual and physiological sensory feedback from mobile wireless platforms. The modular platform facilitates rapid development leading to an increase in prototype testing [4]. Rapid payload conversion between many different surgical tasks is another advantage of the modular design. These types of self-contained surgical devices, which are significantly more transportable and lower in cost than current robotic surgical assistants could ultimately be carried and deployed by non-medical personnel at the site of an injury. A remotely located surgeon could then use these robots to provide critical first response medical intervention irrespective of the location of the patient.

Current research is guided towards evaluating the staple/clamp arm and its ability to provide enough pressure to stop blood flow through a vessel. The tissue interaction during a liver biopsy is also being investigated. Work is being done to create a soft-tissue model to evaluate the performance of end-effectors such as the biopsy grasper. Other payload variations for surgical task assistance are also in the conceptual stages.

Task 2: Development of an "easy to carry" relay system and remote user interface

Digital imaging sensors have been researched and are being implemented into a digital imaging prototype. Human perception of stereovision has been researched with a still image near real-time stereo surgical viewing system being designed and prototyped.

Video from the robot cameras of the planar manipulator robot has been recorded wirelessly using RF during a non-survival animal surgery. A graphical user interface software has also been developed to control the manipulator robots through the Ethernet. This interface has been tested through wired and wireless networks in the lab. The software runs server and client versions. The server version runs on the computer connected to the robots. The client version runs on the remote host computer. A new version of the software has also been developed that can be used to control the camera and image settings of the manipulator robots through the Ethernet. Testing is ongoing to investigate the effect of network delays on robot control. Software is currently being written for use with Falcon 3-D joysticks to control the full mobility robot.

Task 3: Develop procedures and techniques for military use of in vivo robots

Continued benchtop experiments elicited several potential military and clinical applications including immediate exploration, diagnosis, triage, stabilizing treatment, and transmission of medical information. The development of both forward deployed and rear echelon techniques, including the diagnosis and treatment of common conditions specifically to include hemostasis, are currently being performed utilizing trauma models. Ultimately, field deployable in vivo robots, with minimal size and weight, have the capability to positively impact both forward and noncombatant care environments through decreased wound infections, pain, recovery time, and adhesions.

Task 4: Integration and testing

The above subsystems will be continuously integrated via ongoing testing into a deliverable system.

Key Research Accomplishments

- Three planar manipulator robots have been built and demonstrated in benchtop testing and non-survival animal model surgeries.
- Software for adjusting image parameters for the manipulator robots has been developed

- A visual tracking system using the stereo camera pair of the planar manipulator robots is being developed.
- A prototype full mobility shoulder joint with increased speed and dexterity as compared to the planar robot has been built.
- A one-armed robotic manipulator, with the same mobility as a standard laparoscopic tool working through a trocar, has been developed and prototyped.
- Independent joint PID controllers have been developed for the prototype robot. The new control scheme allows for real-time position tracking of a master manipulator which has greatly improved the speed and dexterity of the robot. This design will likely be the basis for future control schemes. The primary challenge with the design of a full mobility robot is meeting the competing design constraints of speed, size, and force.
- Designed, built, and tested a stereo camera circuit board for the prototype manipulator robots.
- Three different payload variations for the wireless mobile platform have been tested with temperature, relative humidity and pressure readings recorded wirelessly in the lab.
- The wireless mobile robot platform has been used to biopsy a sample of ex vivo liver. The same actuation mechanism used for biopsy is being used to test a clamping, suture robot that can deliver a suture to a blood vessel.
- Multiple wireless mobile robots have been used simultaneously to complete various surgical tasks in an animal model.
- Began conceptual thinking behind three new payload variations for the modular robot to help demonstrate more robust surgical task applications possible using the modular wireless modular platform.
- Began development of a model to evaluate performance of robotic end-effectors (such as biopsy) when cutting organ tissue.
- Recorded wireless video of the cameras on the in-vivo proto-type robots using RF transceivers.
- Researched digital imaging sensors.
- Researched human perception stereo vision.
- Designed still image near real-time stereo surgical viewing system.
- Developed a graphical user interface software to control the in vivo prototype robots through the Ethernet.
- Tested the user interface through wired and wireless networks. The software runs server and client versions. The server version is run on the computer connected to the in vivo robot. The client version is run on the remote host computer.
- Developed a new version of the software used to control the camera and image settings from the in vivo robots through the Ethernet. Further ex vivo benchtop testing to investigate the effect of network delays on robot control is ongoing before using the system in an in vivo surgical test.
- Discussed modifications to control and communication electronics for the modular wireless platform.
- Writing software to use the Falcon 3-D joysticks to control the new robot.

Reportable Outcomes

Refereed Journal Publications:

Lehman, A.C., Dumpert, J., Wood, N.A., Redden, L., Visty, A.Q., Farritor, S.M., Varnell, B., Oleynikov, D., "Natural Orifice Cholecystectomy Using a Miniature Robot," *Surgical Endoscopy*, 23(2): 260-266, 2009.

Wood, N., Lehman, A., Dumpert, J., Oleynikov, D., Farritor, S., "A Prototype In Vivo Robotic

System for NOTES," International Journal of Robotics Research Special Issue on Medical Robotics, Submitted.

Lehman, A., Berg, K., Dumpert, J., Wood, N., Visty, A., Rentschler, M., Platt, S., Farritor, S., Oleynikov, D., "Surgery with Cooperative Robots," Computer Aided Surgery, Accepted, Invited.
Lehman, A., Farritor, S., Oleynikov, D., "Role of Robotics in NOTES," Journal of Endourology, Submitted, Invited.

Qadi, A., Goddard, S., Huang, J., Farritor, S., "On Providing Performance Guarantees for an Autonomous Mobile Robot," International Journal of Robotics and Automation, 2008, Submitted.

Dumpert, J., Rentschler, M., Farritor, S., Platt, S., Oleynikov, D., "Stereoscopic In Vivo Surgical Robots," IEEE Sensors Special Issue on In Vivo Sensors for Medicine, Submitted.

Rentschler, M., Platt, S., Berg, K., Dumpert, J., Oleynikov, D., Farritor, S., "Miniature In Vivo Robotics for Remote and Harsh Environments," IEEE Transactions on Information Technology in Biomedicine, 12(1): 66-75, 2008.

Refereed Conference Publications and Presentations:
Lehman, A., Wood, N., Dumpert, J., Oleynikov, D., Farritor, S., "Towards Autonomous Robot-Assisted Natural Orifice Translumenal Endoscopic Surgery," *Proceedings of IMECE2008, 2008 ASME International Mechanical Engineering Congress and Exposition*, October 31-November 6, 2008, Boston, MA.

Lehman, A.C., Wood, N.A., Dumpert, J., Oleynikov, D., Farritor, S.M., "Dexterous Miniature in Vivo Robot for NOTES," in *Proceedings of the 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, Scottsdale, AZ, October, 2008.

Platt, S., Hawks, J., Rentschler, M., Redden, L., Farritor, S., Oleynikov, D.,"Modular Wireless Wheeled In Vivo Surgical Robots," in *Proceedings of the 2008 ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2008)*, Brooklyn, NY, August, 2008.

Qadi, A., Goddard, S., Huang, J., Farritor, S., "Using Dynamic Processing Windows for Robot Group Control," IEEE International conference on Robotics and Automation, Pasadena, CA, May, 2008.

Lehman, A., Wood, N., Dumpert, J., Oleynikov, D., Farritor, S., "Robotic Natural Orifice Translumenal Endoscopic Surgery," IEEE International Conference on Robotics and Automation, *Pasadena*, CA, May, 2008.

Medical Conference Publications and Presentations:
Hawks, J., Rentschler, M., Farritor, S., Oleynikov, D., Platt, S., “A Modular Wireless In Vivo Surgical Robot with Multiple Surgical Applications” *Studies in Health Technology and Informatics - Medicine Meets Virtual Reality Conference*, Long Beach, CA, January 2009.

James, E., Lehman, A., Farritor, S., Oleynikov, D., "Robotics and NOTES - A Match Made in Heaven," Digestive Diseases Week 2008, May 17 - 22, 2008, San Diego Convention Center, San Diego, CA.

Lehman, A., Dumpert, J., Wood, N., Visty, A., Farritor, S., Varnell, B., Oleynikov, D., "Natural Orifice Translumenal Endoscopic Surgery with a Miniature In Vivo Surgical Robot [Video]," 2008 Annual Meeting of The Society of American Gastrointestinal and Endoscopic Surgeons, Philadelphia, PA, April 2008.

Lehman, A., Dumpert, J., Visty, A., Rentschler, M., Farritor, S., Oleynikov, D., "Toward Natural Orifice Surgery with Cooperative Miniature Robots," 2008 Annual Meeting of The Society of American Gastrointestinal and Endoscopic Surgeons, Philadelphia, PA, April 2008.

Lehman, A., Dumpert, J., Wood, N., Redden, L., Visty, A., Farritor, S., Varnell, B., Oleynikov, D., "Natural Orifice Cholecystectomy Using a Miniature Robot," 2008 Annual Meeting of The Society of American Gastrointestinal and Endoscopic Surgeons, Philadelphia, PA, April 2008,

Conclusion

Our long-term goal, to use image guided miniature robots to convert many open and laparoscopic surgeries to the NOTES approach, can be realized through the development of a family of in vivo robots. Completion of the current statement of work is a critical first step toward this effort as it builds on previous successes and focuses on developing an image-guided robot capable of provisions of basic diagnosis and triage.

Several functional prototypes capable of tissue manipulation, abdominal exploration, and surgical utilization have been developed. This revolutionary, robotic technology has demonstrated its applicability in natural orifice and single incision minimally invasive surgical procedures. Such procedures are virtually impossible to perform without the design and creation of new tools like our miniature robots.

The small, disposable, in vivo robots developed in this study may enable lifesaving diagnosis and triage in more forward military environments. The second phase of this project will focus on continued in vivo testing as well as the acquisition of regulatory approval. The portability and survivability of our technology in forward, rugged situations is a substantial challenge to be met through continued trauma model testing and prototype development. This will have a direct impact on combat medical care thus matching TATRC’s Research Area of Interest B, Combat Casualty Care Research Program. The new robotic technology will also be useful in many levels of military medical care as well as significantly impacting the application of NOTES everywhere.

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2. Lehman, A.C., Dumpert, J., Wood, N.A., Redden, L., Visty, A.Q., Farritor, S.M., Varnell, B., Oleynikov, D., "Natural Orifice Cholecystectomy Using a Miniature Robot," *Surgical Endoscopy*, 23(2): 260-266, 2009.
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4. Hawks, J., Rentschler, M., Farritor, S., Oleynikov, D., Platt, S., “A Modular Wireless In Vivo Surgical Robot with Multiple Surgical Applications” *Studies in Health Technology and Informatics - Medicine Meets Virtual Reality Conference*, Long Beach, CA, January 2009.

Appendices

1. Lehman, A.C., Wood, N.A., Dumpert, J., Oleynikov, D., Farritor, S.M., "Dexterous Miniature in Vivo Robot for NOTES," in *Proceedings of the 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, Scottsdale, AZ, October 2008.
2. Lehman, A.C., Dumpert, J., Wood, N.A., Redden, L., Visty, A.Q., Farritor, S.M., Varnell, B., Oleynikov, D., "Natural Orifice Cholecystectomy Using a Miniature Robot," *Surgical Endoscopy*, 23(2): 260-266, 2009.
3. Platt, S., Hawks, J., Rentschler, M., Redden, L., Farritor, S., Oleynikov, D.,"Modular Wireless Wheeled In Vivo Surgical Robots," in *Proceedings of the 2008 ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2008)*, Brooklyn, NY, August, 2008.
4. Hawks, J., Rentschler, M., Farritor, S., Oleynikov, D., Platt, S., “A Modular Wireless In Vivo Surgical Robot with Multiple Surgical Applications” *Studies in Health Technology and Informatics - Medicine Meets Virtual Reality Conference*, Long Beach, CA, January 2009.

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Dexterous Miniature *In Vivo* Robot for NOTES

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Abstract— The complete elimination of external incisions through natural orifice access to the peritoneal cavity is potentially the next step in reducing the invasiveness of surgery. Natural Orifice Translumenal Endoscopic Surgery (NOTES) provides distinct patient advantages, but is surgically challenging. For the NOTES approach to be applied routinely, devices need to be developed that provide the surgeon with a stable multi-tasking platform for tissue manipulation and visualization. Much research towards device development for NOTES is based on the flexible endoscopy platform. However, these tools remain constrained by the entry incision and are further limited by challenges in tool triangulation, and multi-tasking capabilities. An alternative approach is the use of miniature *in vivo* robots that can be fully introduced into the peritoneal cavity through a natural orifice. A robotic platform for NOTES is being developed that attempts to emulate laparoscopic capabilities and control. This paper presents the prototype design of this platform and *in vivo* feasibility studies in non-survivable animal model procedures.

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I. INTRODUCTION

Laparoscopy revolutionized general surgery beginning in the 1990s, and many procedures that were previously performed through a large, open incision are now performed using minimally invasive techniques. These techniques have generally proven safer with improved patient outcomes. Natural Orifice Translumenal Endoscopic Surgery (NOTES) is a new alternative to abdominal surgery that combines endoscopy and laparoscopic techniques to completely eliminate external incisions. Theoretically, NOTES offers significant patient advantages from the elimination of complications associated with external incisions, including wound infections, pain, and hernia formation, as well as reducing adhesions, and improving cosmetics and recovery times [1], [2].

The first animal model study demonstrating the efficacy of a peroral transgastric endoscopic approach to the peritoneal cavity was reported by Kalloo *et al*. in 2004 [3]. Subsequent transgastric survival studies include ligation of fallopian tubes [4], peritoneal exploration with organ resection [5], gastrojejunal anastomosis [6], [7] partial hysterectomy [8], lymphadenectomy [9], and oophorectomy and tubectomy [10]. Alternative methods for accessing the peritoneal cavity have also been evaluated including the transvesical and transcolonic approach [10], [11].

The transvaginal and transgastric NOTES approaches have also been demonstrated in multiple human cases. Rao *et al* have successfully attempted the translumenal approach for 17 cases including appendectomy, liver biopsy, and tubal ligation [12]. Additional cases including hybrid transvaginal laparoscopically-assisted cholecystectomies [13], [14], transvaginal cholecystectomy [15], [16], transgastric cholecystectomy [17], and percutaneous endoscopic gastrotomy (PEG) rescue [18] have also been reported. Current feasibility studies include flexible transgastric peritoneoscopy with liver biopsy during laparoscopic gastric bypass surgery [19], and endoscopic peritoneoscopy [20]. While these studies have demonstrated the feasibility of a NOTES approach, significant constraints have also been identified with using a flexible endoscopy platform, including the relative inability to apply off-axis forces, inadequate triangulation, and limitations in passing multiple instruments simultaneously into the peritoneal cavity through a single incision [21].

Much of the focus for addressing the limitations of working through a natural orifice is currently directed toward the further refinement of the flexible endoscopy platform. For example, the ViaCath System is currently being developed as an endoluminal NOTES robotic system

[22]. The first generation system consists of a master console with haptic interfaces, slave drive mechanisms, and flexible instruments located alongside a standard gastroscope or endoscope. A second generation system with a shoulder-elbow configuration similar to the human arm is currently being developed at Purdue University.

Further, a four-channel platform scope using Shapelock® technology, called the TransPort™ EndoSurgical Operating Platform (USGI Medical, San Capistrano, CA) has been developed [23]. This system has two states providing flexibility for insertion through the gastrointestinal tract and locking capabilities with distal tip maneuverability once positioned The four operating channels accommodate two 6mm and two 4mm instruments. The EndoSurgical Operating System™, including the TransPort™ operating platform, is available commercially.

An alternative approach to addressing the limitations of the flexible endoscopy platform is the use of *in vivo* robots. In contrast to many other surgical robots, *in vivo* robots are fully inserted into the peritoneal cavity. Once inserted, these robots are no longer constrained by the entrance incision or the geometry of the natural lumen. This allows the surgeon to arbitrarily position the robots within each quadrant of the peritoneal cavity for visualization and task assistance. Further, multiple devices can be inserted into the peritoneal cavity through the same access point.

For example, the Magnetic Anchoring and Guidance System (MAGS) uses multiple instruments, including tissue retractors and cautery dissectors that are deployed through a single access port [24]. Magnetic coupling between each instrument and an external handheld magnet hold the device to the interior abdominal wall. Once each instrument is positioned, the handheld magnet can be replaced with an 18 gauge percutaneous, threaded needle anchor. The MAGS used with an endoscope has successfully demonstrated transgastric, transcolonic, and transvaginal non-survivable cholecystectomies in porcine models. Two non-survivable porcine nephrectomies using MAGS instruments and a single 15-mm transumbilical trocar have also been demonstrated [25]. Similarly, a preliminary procedure using three miniature *in vivo* robots, including a peritoneum-mounted imaging robot, a lighting robot, and a retraction robot has demonstrated the feasibility of developing a robotic platform using cooperative robots with sufficient functionality for performing NOTES procedures [26].

Further, mobile *in vivo* robots promise to provide a remotely controlled, maneuverable platform for vision and surgical task assistance. The basic design of a mobile robot consists of two independently driven helical-profiled wheels providing forward, reverse, and turning maneuverability, and a tail to prevent counter-rotation. This basic platform with visualization and task assistance capabilities has been demonstrated in multiple porcine model laparoscopic procedures. A mobile robot has also successfully demonstrated transgastric access to the peritoneum with sufficient mobility to traverse within the gastric and peritoneal cavities [27].

II. *In Vivo* Robotic Platform for NOTES

A. *Robot Design Overview*

An *in vivo* miniature robot can be inserted through the lumen of the intestinal tract using the upper approach. Once fully inserted, the robot can be used within the peritoneal cavity without the constraints of an externally actuated endoscopic device. The robotic platform attempts to emulate laparoscopic control and capabilities for NOTES procedures using an external control console that is magnetically coupled with the *in vivo* robot.

Two control consoles have been developed for the *in vivo* robot. The first uses two standard laparoscopic tool handles as the surgical interface for control of the robot. The second uses two joysticks in place of the laparoscopic tool handles. For each control console, an LCD screen located at the center of the console displays video feedback from the robot located directly below within the peritoneal cavity. The base of the control console contains magnets that couple with magnets embedded in the robot for attaching the robot to the upper abdominal wall, and for positioning of the robot. Alternatively, an external magnetic handle may be placed on the exterior surface of the abdomen for attachment of the robot.

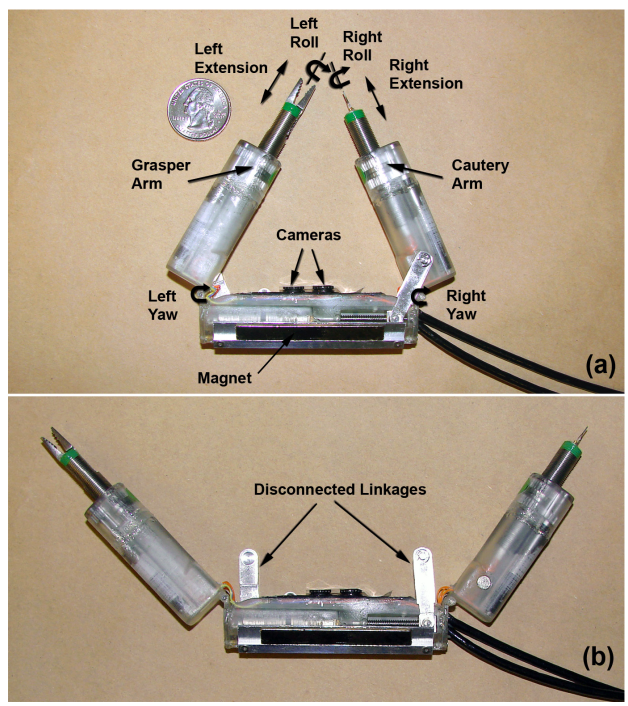

Figure 1. NOTES robot in articulation (upper) and insertion (lower) configurations.

The basic design of the robot for NOTES, shown in Fig. 1, consists of a central "body" and two "arms", with configurations for insertion and articulation. The body houses two motors coupled with a lead screw that translate a nut in a guide to articulate the shoulder joint. Also contained within the body are two cameras for visualization and an ultrabright white LED for lighting of the surgical environment.

Each arm consists of an upper arm and a lower arm. The lower arm extends, retracts, and rolls with respect to the upper arm. The upper arm is connected to the body by a 1-DOF shoulder joint. In the insertion configuration, the linkage used for articulation of the shoulder joint is disconnected, allowing flexibility at the shoulder joint for insertion through the complex geometry of the natural lumen. Once inserted, the linkage is reconnected to provide a stable platform for articulation. Currently, endoscopic tools assist in reconnecting the linkage. In future prototypes the robot will reconfigure independently.

B. *Design Constraints*

For the robot to perform a surgical intervention, the necessary forces and velocities must be determined. Research has been performed using a specialized device called the BlueDRAGON to measure the forces, torques, and displacements applied by surgeons in performing a laparoscopic cholecystectomy [28]. Based on this work, it was determined that the robot should be able to apply forces along the axis of the tool and perpendicular to this axis of 10N and 5N, respectively. Also, the angular velocities about the tool axis and the perpendicular axes should be on the order of 1rad/s and 0.4rad/s., respectively. It is important to note that the BlueDRAGON system measures the force applied by the surgeon and not the *in vivo* forces applied to the tissue. The actual force at the tissue is influenced by the friction of the trocar and reaction with the abdominal wall. The forces applied by the surgeon are undoubtedly greater than the minimum force necessary to accomplish the task.

The design of a robot to enable natural orifice surgical procedures is influenced by the competing preferences of size, speed, and strength. Ideally, a robot for NOTES is small, fast, and strong. Preliminary robot designs developed to evaluate the feasibility of a miniature *in vivo* robot platform for NOTES will be of the proper size to fit within a 25mm inner diameter overtube for natural orifice insertion, and with sufficient strength to apply 10N along the axis of each arm, and 5N perpendicular to the arm. These size and strength design constraints are met at the expense of speed.

III. Kinematic Design and Modeling

Three iterations of the NOTES robot platform have been developed. Each of the designs follow a similar method for evaluation of the kinematic design. The first two iterations are detailed in previous publication submissions [29], [30]. This paper focuses on analysis of the third NOTES robot prototype.

The kinematic model for the right half of the NOTES robot with prismatic arms is shown in Fig. 2. This robot is a 3-DOF planar manipulator with a rotational shoulder joint, and a prismatic arm joint with rotation. The joint variables are pitch, yaw, and lower arm extension, denoted by α_1, θ_3, and a_3, respectively. The Denavit-Hartenerg parameters are given in Table I. A universal frame {0} introduces gravity, with the parameter, α_0, defining the rotation of the robot with respect to the universal frame. The parameter, α_1, defining the angle of rotation of the cameras with respect to frame {1} is zero. Parameters a_2 and a_4 are constants defining the half body width and the end effector offset with respect to the shoulder joint, respectively. The lower arm extension (a_3), and shoulder yaw (θ_3), range from 64-93mm and 75-154º, respectively.

Analyses were performed to determine the necessary joint torques and forces. All analyses assume a half body width (a_2) of 40mm and a prismatic link mass of 30g with a workplane (α_0) of 40 degrees below level.

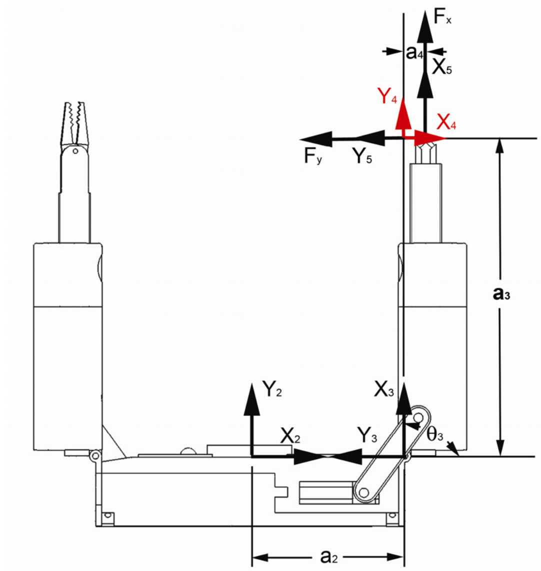

Figure 2. Kinematic model of the NOTES robot.

TABLE 1
Denavit-Hartenberg Parameters

i	α_{i-1}	a_{i-1}	θ_i	d_i
1	α_0	0	0	0
2	α_1	0	0	0
3	0	a_2	θ_3	0
4	0	a_3	-90	0
5	0	a_4	90	0

A. *Shoulder Joint*

Using the general kinematic model and the Denavit-Hartenberg parameters, the location of the end effector in frame {1} is defined and used to derive the Jacobian of the robot, as given in equations (1) and (2-3), respectively.

$$ {}^{1}P_{Org5} = \begin{bmatrix} \cos(\theta_3)a_3 + \sin(\theta_3)a_4 + a_2 \\ \cos(\alpha_1)\sin(\theta_3)a_3 - \cos(\alpha_1)\cos(\theta_3)a_4 \\ \sin(\alpha_1)\sin(\theta_3)a_3 - \sin(\alpha_1)\cos(\theta_3)a_4 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (1) $$

$$ J(q_1, q_2, q_3) = J(\alpha_1, \theta_3, a_3) = \frac{\partial}{\partial q_i} {}^{1}P_{Org4} \quad (2) $$

$$
{}^{1}J = \begin{bmatrix} 0 & -\sin(\theta_3)a_3 + \cos(\theta_3)a_4 & \cos(\theta_3) \\ -\sin(\alpha_1)\sin(\theta_3)a_3 + \sin(\alpha_1)\cos(\theta_3)a_4 & \cos(\alpha_1)\cos(\theta_3)a_3 + \cos(\alpha_1)\sin(\theta_3)a_4 & \cos(\alpha_1)\sin(\theta_3) \\ \cos(\alpha_1)\sin(\theta_3)a_3 - \cos(\alpha_1)\cos(\theta_3)a_4 & \sin(\alpha_1)\cos(\theta_3)a_3 + \sin(\alpha_1)\sin(\theta_3)a_4 & \sin(\alpha_1)\sin(\theta_3) \end{bmatrix} \quad (3)
$$

From the principle of virtual work, the Jacobian transpose maps Cartesian forces applied by the end effector into equivalent joint torques. The shoulder joint torque necessary to apply a force, F_x of 10N and F_y of 5N in the x and y-directions of frame {5}, respectively were determined. The joint torques throughout the robot workspace are shown in Fig. 3, with a maximum required shoulder joint torque of 522mNm.

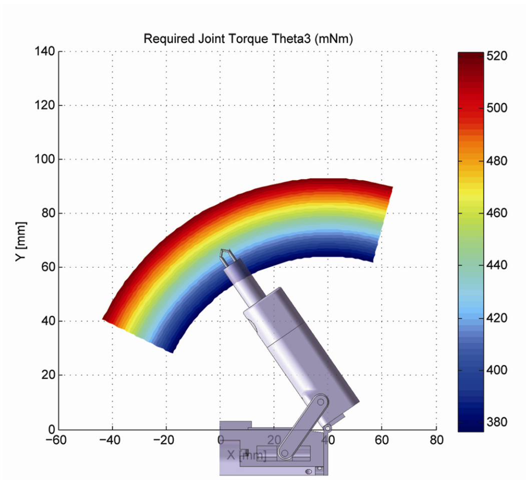

Figure 3. Shoulder joint torque required throughout workspace to apply forces at the end effector tip of 10N and 5N along the axes parallel and perpendicular to the robot arm, respectively.

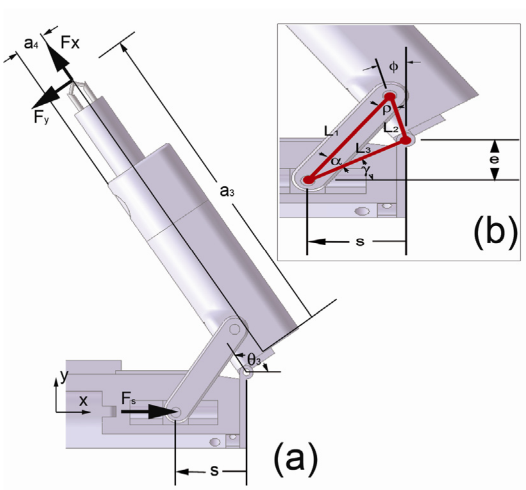

Figure 4. Kinematic model of robot shoulder joint showing applicable forces (a) and linkage geometry (b).

The necessary input force, F_s, to apply the necessary shoulder joint torque was then determined using a kinematic model of the shoulder joint shown in Fig. 4. In this mechanism, a lead screw applies a force, F_s, to a slider constrained to move only in the x-direction. The slider mechanism is coupled to the robotic arm, a_3, by a link, L_1, with rotational degrees of freedom at each end.

From this schematic, the input force required from the lead screw to apply forces, F_x and F_y, at the end effector were determined and are shown in Fig. 5.

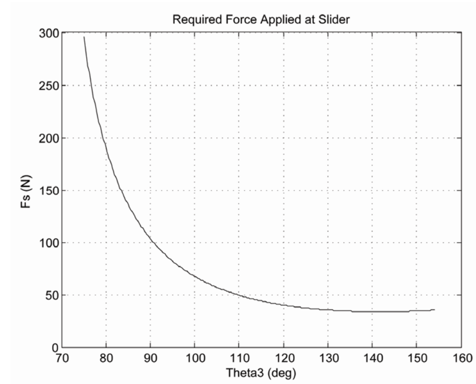

Figure 5. Input force required to apply forces at the end effector tip of 10N and 5N along the axes parallel and perpendicular to the robot arm, respectively.

It is desired that the robot be able to apply the end effector forces within the workspace range of joint angle, θ_3, from 110-154º. This enables the robot to manipulate tissue within the bimanual workspace while still allowing access for each arm to its entire workspace. The maximum slider force input is used to determine the appropriate motor for driving the shoulder joint. From analysis of Fig. 5, the maximum slider input force required is 67N. Assuming an overall efficiency of fifty percent, with losses being due to friction, the input motor torque required is 13.6mNm. An 8mm PMDC motor with a 64:1 gearhead was chosen for this application. The theoretical maximum shoulder joint torque and angular velocity with this motor are shown in Fig. 6.

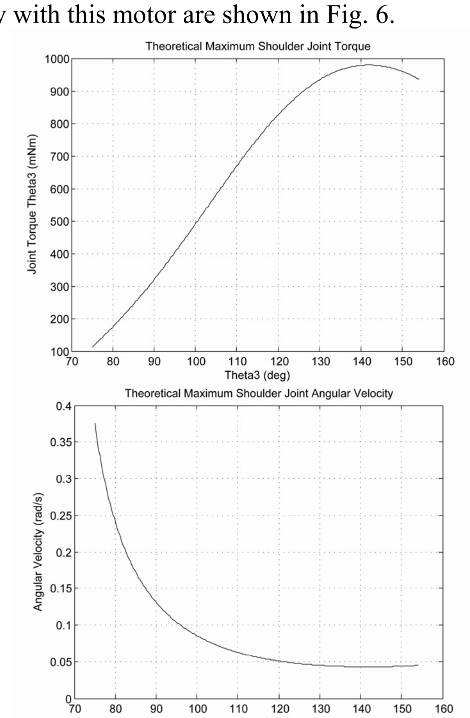

Figure 6. Theoretical maximum shoulder joint torque (mm) and angular velocity (rad/s).

B. Prismatic Arm Joint

Extension and retraction of the prismatic joint is accomplished using a 6mm PMDC motor with a 64:1 gearhead. The motor transmits torque to rotate the lead screw through a series of two spur gears. The force applied by the end effector is capable of applying a force in excess of the necessary force, F_x, of 10N. The theoretical speed for the extension and retraction of the arm is approximately 0.75 mm/s.

IV. In Vivo Results

Three iterations of the dexterous miniature robot for NOTES have been prototyped and evaluated in independent non-survivable procedures in a porcine model. Each procedure was performed at the University of Nebraska Medical Center with experimental protocols approved by the institutional review committee.

A basic procedure using the NOTES robot platform is initiated with using a needle knife to form a gastrotomy. An overtube is then advanced using a standard therapeutic endoscope through the esophagus and up to the transgastric incision. The robot in its insertion configuration is then inserted through the overtube and into the peritoneal cavity using the endoscope.

The feasibility of natural orifice insertion was successfully demonstrated in the first non-survivable porcine model procedure. Once fully inserted into the peritoneal cavity, the robot is lifted from the floor of the peritoneal cavity using the magnetic coupling between the external control console and the magnets embedded in the robot body, as shown in Fig. 7. The surgeon can then maneuver the control console along the exterior surface of the abdomen with the robot maintaining position with respect to the control console. For each procedure, the surgeon explored each quadrant of the peritoneal cavity using the on-board robot cameras. In the first procedure, a small bowel target was identified and dissected.

Subsequent procedures focused on evaluating the functionality of the robot for performing a cholecystectomy. For these studies, the robot was inserted through a transabdominal incision, with gross tissue retraction and supplementary visualization being provided by the laparoscope. Following positioning of the robot, the grasper end effector was oriented and extended to grasp the cystic duct. The cautery arm was then positioned and extended for dissection. A view from an on-board camera of this task is shown in Fig. 8. Iterations of this stretch and dissect task were performed to remove the gallbladder from its hepatic attachments.

The configurable design of the robot allowed sufficient flexibility for insertion through the natural orifice and provided a stable platform for off-axis tissue visualization and manipulation once fully inserted into the peritoneal cavity. Locating the cameras between the two arms of the robot improved tool triangulation and provided a more intuitive understanding of the surgical environment.

Figure 7. NOTES robot in the peritoneal cavity.

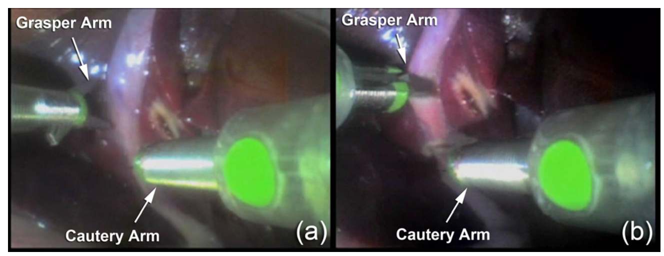

Figure 8. Stretch and dissect of cystic duct as viewed from a robot camera.

V. Conclusion

A transgastric approach using standard endoscopic techniques facilitates on-axis access to the lower abdominal organs, making transgastric procedures that do not require a retroflexed position feasible. However, studies demonstrating the performance of upper abdominal procedures including cholecystectomy, have proven complicated due to image instability and the difficulty of simultaneously manipulating the endoscope and observing the area being manipulated.

The kinematic analysis of a NOTES robot demonstrated that it is feasible to apply significant force for tissue manipulation. Further, the successful *in vivo* demonstrations of the robot prototypes suggest the feasibility of using miniature *in vivo* robots to perform natural orifice procedures in the peritoneal cavity. The design of the robot enabled flexibility for insertion through the natural lumen, and once deployed provided an adequate platform for tissue manipulation from multiple orientations. The visual feedback provided by the on-board cameras and the ability to easily reposition the robot enabled the surgeon to explore and manipulate within the each quadrant of the peritoneal cavity.

Continuing improvements to the robot platform are being pursued including improving dexterity and increasing speed. Also, cooperative robots are being developed with additional functionalities to provide the surgeon with the necessary functionality to perform a NOTES cholecystectomy using only miniature *in vivo* robots.

ACKNOWLEDGMENT

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Natural orifice cholecystectomy using a miniature robot

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Abstract
Background Natural orifice translumenal endoscopic surgery (NOTES) is surgically challenging. Current endoscopic tools provide an insufficient platform for visualization and manipulation of the surgical target. This study demonstrates the feasibility of using a miniature in vivo robot to enhance visualization and provide off-axis dexterous manipulation capabilities for NOTES.
Methods The authors developed a dexterous, miniature robot with six degrees of freedom capable of applying significant force throughout its workspace. The robot, introduced through the esophagus, completely enters the peritoneal cavity through a transgastric insertion. The robot design consists of a central "body" and two "arms" fitted respectively with cautery and forceps end-effectors. The arms of the robot unfold, allowing the robot to flex freely for entry through the esophagus. Once in the peritoneal cavity, the arms refold, and the robot is attached to the abdominal wall using the interaction of magnets housed in the robot body with magnets in an external magnetic handle. Video feedback from the on-board cameras is provided to the surgeon throughout a procedure.
Results The efficacy of this robot was demonstrated in three nonsurvivable procedures in a porcine model, namely, abdominal exploration, bowel manipulation, and cholecystectomy. After insertion, the robot was attached to the interior abdominal wall. The robot was repositioned throughout the procedure to provide optimal orientations for visualization and tissue manipulation. The surgeon remotely controlled the actuation of the robot using an external console to assist in the procedures.
Conclusion This study has shown that a dexterous miniature in vivo robot can apply significant forces in arbitrary directions and improve visualization to overcome many of the limitations of current endoscopic tools for performing NOTES procedures.

Keywords Cholecystectomy · Surgical, technical

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Laparoscopy revolutionized general surgery beginning in the 1990s, and many procedures that previously were performed through a large open incision currently are performed using minimally invasive techniques. These techniques generally have proved to be safer, with improved patient outcomes.

Natural orifice translumenal endoscopic surgery (NOTES) is a new alternative to abdominal surgery that uses endoscopic techniques to attempt complete elimination of external incisions. Theoretically, NOTES offers significant patient advantages by eliminating complications associated with external incisions including wound infections, pain, and hernia formation, and by reducing adhesions, improving cosmetics, and shortening recovery times [1, 2].

The first study in an animal model to demonstrate the safety and feasibility of a peroral transgastric endoscopic approach to the peritoneal cavity was reported by Kalloo et al. [3] in 2004. This study consisted of 12 acute and 5 survival procedures, including examination of the peritoneal cavity biopsy of the liver. Subsequent survival studies using transgastric access include ligation of fallopian tubes [4], peritoneal exploration with organ resection [5], gastrojejunal anastomosis [6, 7] partial hysterectomy [8], lymphadenectomy [9], and oophorectomy and tubectomy [10]. Alternative methods for accessing the peritoneal cavity also have been evaluated including the transvesical and transcolonic approaches [10, 11].

Multiple transvaginal and transgastric NOTES procedures also have been performed in humans successfully. Rao et al. [12] have successfully attempted the transluminal approach for 17 cases including appendectomy, liver biopsy, and tubal ligation. Additional case reports include hybrid transvaginal laparoscopically assisted cholecystectomy [13, 14], transvaginal cholecystectomy [15, 16], transgastric cholecystectomy [17], and percutaneous endoscopic gastrotomy (PEG) rescue [18]. Feasibility studies include flexible transgastric peritoneoscopy with liver biopsy during laparoscopic gastric bypass surgery [19] and endoscopic peritoneoscopy [20].

Although these studies have demonstrated the feasibility of a NOTES approach, significant constraints also have been identified with the use of a flexible endoscopy platform, including a relative inability to apply off-axis forces, inadequate triangulation, and limitations in passing multiple instruments simultaneously into the peritoneal cavity [21].

Much work toward addressing these constraints currently is focused on further refinement of the flexible endoscopy platform. For example, the ViaCath System currently is being developed as an endoluminal NOTES robotic system [22]. The first-generation system consists of a master console with haptic interfaces, slave drive mechanisms, and flexible instruments located alongside a standard gastroscope or endoscope. A second-generation system with a shoulder–elbow configuration similar to the human arm currently is under development at Purdue University.

Furthermore, the TransPort EndoSurgical Operating Platform (USGI Medical, San Clemente, CA, USA) is four-channel platform scope based on the Shapelock locking technology (USGI Medical, San Clemente, CA) [23]. The TransPort has a flexible state allowing for insertion of the device through the gastrointestinal tract. Once positioned, the base of the endoscope can be locked into position while allowing the distal operating tip to be steered freely. The TransPort contains four operating channels that accommodate two 6-mm and two 4-mm instruments. The EndoSurgical Operating System, including the TransPort operating platform, is available commercially.

An alternative approach to addressing the limitations of the flexible endoscopy platform is the use of in vivo robots that can be inserted through the natural lumen of the intestinal tract. These devices can access the peritoneal cavity through a transgastric, transcolonic, or transvaginal incision. Once fully inserted, these robots are no longer constrained by the entrance incision or the geometry of the lumen. This enables the surgeon to position the robots within each quadrant of the peritoneal cavity for visualization and task assistance. Furthermore, multiple devices can be inserted into the peritoneal cavity through the same access point.

For example, the Magnetic Anchoring and Guidance System (MAGS) uses multiple instruments, including tissue retractors and cautery dissectors, deployed through a single access port [24]. Each instrument is attached to and positioned along the interior abdominal wall using magnetic coupling of magnets embedded in the instruments with an external handheld magnet. Once each instrument is positioned, the handheld magnet can be replaced with an 18-gauge percutaneous, threaded needle anchor. The MAGS together with an endoscope has been used successfully for transgastric, transcolonic, and transvaginal nonsurvivable cholecystectomies in porcine models.

Similarly, a preliminary procedure using three miniature in vivo robots including a peritoneum-mounted imaging robot, a lighting robot, and a retraction robot has demonstrated the feasibility of developing a robotic platform using cooperative robots with sufficient functionality for performing NOTES procedures [25].

Furthermore, mobile in vivo robots provide a remotely controlled, maneuverable platform for vision and surgical task assistance. The basic design of a mobile robot consists of two independently driven helical-profiled wheels providing forward, reverse, and turning maneuverability, and a tail to prevent counter-rotation. This basic platform with visualization and task assistance capabilities has been demonstrated in multiple animal model laparoscopic procedures. A mobile robot also has successfully demonstrated transgastric access to the peritoneum with sufficient traverse mobility in the gastric and peritoneal cavities [26].

Materials and methods

The robotic platform for NOTES, shown in Fig. 1, consists of a miniature in vivo robot inserted fully into the peritoneal cavity through a natural orifice, a surgeon control console, and an external magnetic handle.

The basic design of the dexterous miniature robot for NOTES, shown in Figs. 2 and 3, consists of two “arms” connected to a central “body” by a rotational “shoulder” joint. The body of the robot contains a stereovision pair for providing visualization of the surgical field. Each arm is composed of upper and lower arms, with the lower arm

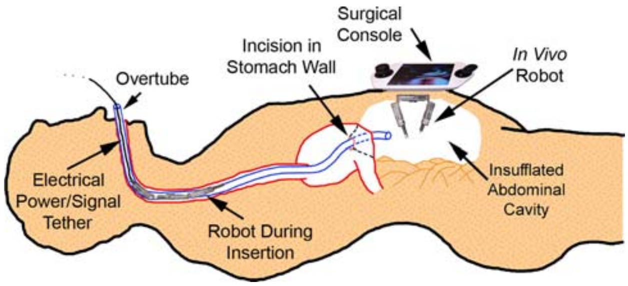

Fig. 1 Natural orifice surgery using a miniature in vivo robot platform

extending and retracting from the upper arm. The cautery end effector can be retracted fully into the upper arm for insertion. With the second-generation robot, the lower arm also rotates with respect to the upper arm. The right arm is fitted with a cautery and the left lower arm with a grasper end effector. The mass of the robot is approximately 110 g.

The robot has two configurations enabling flexibility for natural orifice insertion and rigidity for tissue manipulation. In the articulation configuration, a linkage connecting the body and the upper arm is used to rotate the shoulder joint. For insertion, this linkage is decoupled magnetically from the upper arm, allowing each arm to rotate freely at the shoulder joint. Once the robot is fully inserted into the peritoneal cavity, the linkages are reconnected with the assistance of endoscopic tools. In future designs, the robot will self-assemble for articulation and disassemble for robot removal.

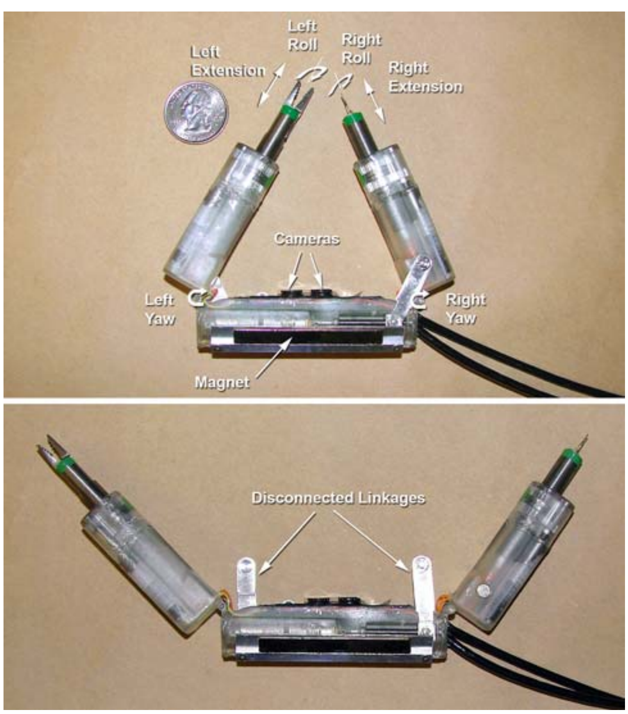

Fig. 2 Natural orifice translumenal endoscopic surgery (NOTES) robot in articulation (*upper*) and insertion (*lower*) configurations

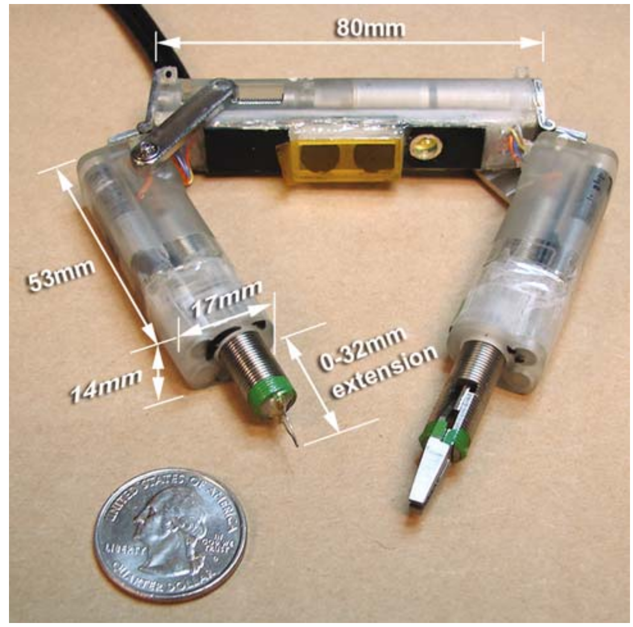

Fig. 3 Approximate dimensions of a natural orifice translumenal endoscopic surgery (NOTES) robot

The body of the robot contains embedded magnets that couple with magnets in an external handle or the surgeon console for attachment of the robot to the interior abdominal wall. The exterior magnet handle can be moved along the outer surface of the abdomen for gross repositioning of the robot throughout the procedure. The handle also can be used to deform the abdominal wall, allowing for an additional degree of freedom. This attachment method enables the surgeon to position the robot to obtain views and workspaces within each quadrant of the peritoneal cavity without necessitating an additional endoscope or retroflexed position. The body of the robot also contains three embedded eyelets that allow the surgeon to suture the robot to the abdominal wall.

The surgeon console, shown in Fig. 4, consists of two analog joysticks, each with three degrees of freedom, for controlling the manipulation of the robot arms. The gripper joystick also has two pushbutton controls for opening and closing the grasper jaws. An 8-in. TFT color LCD monitor is located between the two joysticks to display the video from the robot cameras. A foot pedal is used to activate the cautery capability. The design of the surgeon console together with the robot provides essentially a laparoscopic platform for performing NOTES procedures.

Iterations of the dexterous miniature robots for NOTES have been prototyped and tested in three nonsurvivable animal model studies. The procedures were performed at the University of Nebraska Medical Center with experimental protocols approved by the institutional review committee. The weight of the pigs varied from 60 to 80 lb.

Fig. 4 Surgeon console used for control of the natural orifice translumenal endoscopic surgery (NOTES) robot

For each procedure, the pig was fed Gatorade and water for 36 h before the procedure.

The basic procedure was initiated with the creation of a standard natural orifice gastrotomy using a needle knife. An overtube with an external diameter of 27 mm then was inserted through a transesophageal incision and advanced up to the gastrotomy. The robot was configured for insertion and advanced into the peritoneal cavity using a standard therapeutic endoscope. The endoscope was used throughout the procedure to provide retraction and supplementary visualization. Two of the procedures focused on evaluating the functionality of the robot. For these procedures, the robot was inserted into the peritoneal cavity through a transabdominal incision, with gross tissue retraction provided by an articulating fan retractor and supplementary visualization by a standard laparoscope.

In the first procedure, the robot was lifted from the floor of the peritoneal cavity using the external magnetic handle composed of two magnets, each with a surface field of 6,645 Gauss. The surgeon then maneuvered the handle to explore each quadrant of the peritoneal cavity using the on-board cameras and to identify a small bowel target for tissue manipulation. The robot then was positioned for dissection, and the grasper arm was extended to grasp the tissue. The grasper arm retracted the tissue to allow access for the cautery arm. The shoulder of the cautery arm then was rotated, and the cautery was extended for cauterization of the small bowel. The lower arm of this robot could not rotate, thus limiting the surgeon's dexterity for performing cholecystectomy. At the end of the procedure, the robot could be retrieved by pulling its tether through the hole initially used for its insertion.

In subsequent procedures, the surgeon used the dexterous robot to attempt cholecystectomy. Again, the surgeon used magnetic coupling to attach the robot to the interior abdominal wall and manipulated the exterior magnetic handle to explore each quadrant of the peritoneal cavity. The robot then was positioned for the cholecystectomy using the external magnetic handle, as shown in Fig. 5. Next, the grasper end effector was oriented and extended to grasp the cystic duct. The cautery end effector then was moved into position for dissection and division of the

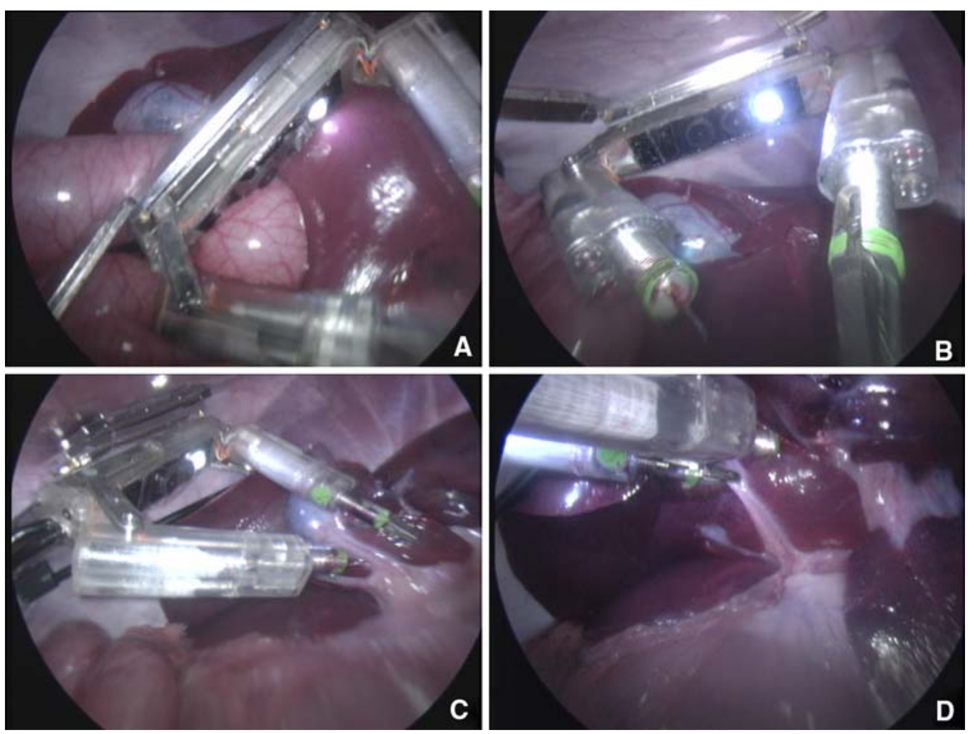

Fig. 5 Laparoscopic view of the robot attachment (**A** and **B**) and positioning (**C** and **D**) using magnetic coupling with the external magnetic handle during the third animal model procedure

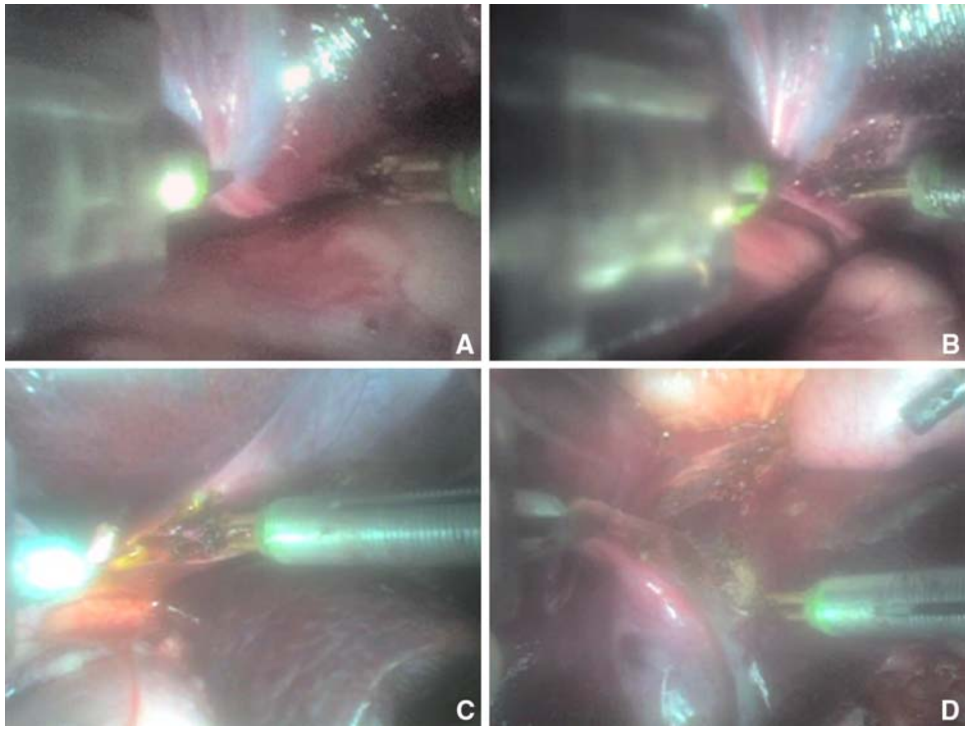

Fig. 6 Robot camera view during the second animal model procedure of grasping the gallbladder (**A**), beginning dissection (**B**), severing the cystic duct (**C**), and dissecting the gallbladder from the hepatic attachments (**D**)

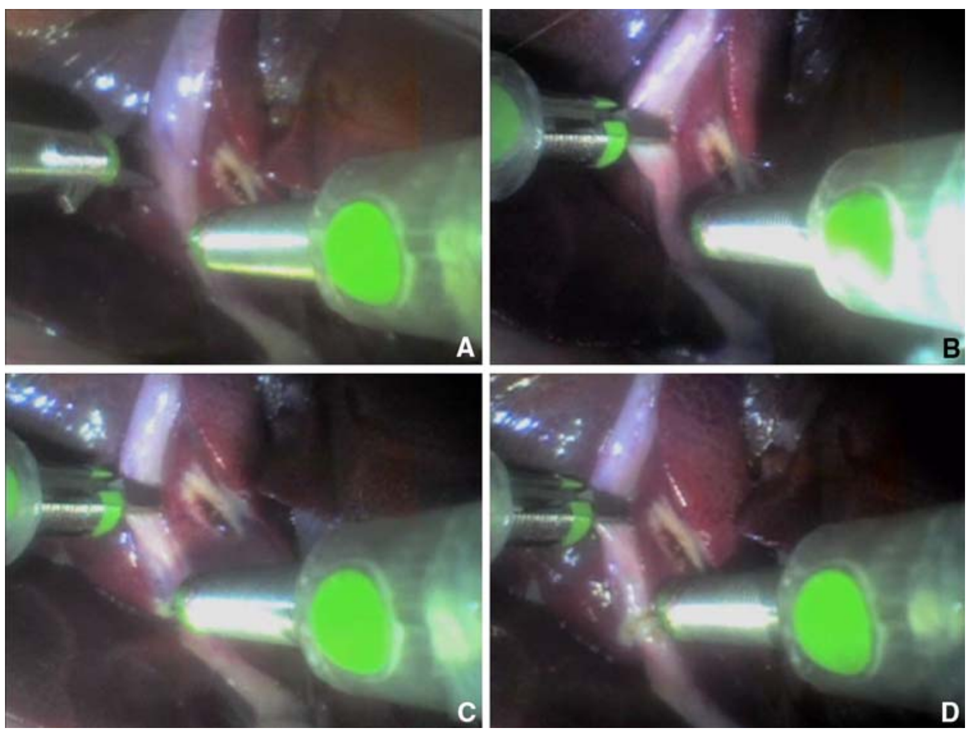

Fig. 7 Robot camera view during the third animal model procedure of positioning the grasper (**A**), grasping (**B**), and dissecting (**C** and **D**)

cystic duct. Dissection continued through iterations of the stretch and dissection task, with the gallbladder being removed from its hepatic attachments. Views from the robot cameras of the gallbladder dissection for the second and third robot procedures are shown in Figs. 6 and 7, respectively.

Results

These nonsurvivable animal model studies using a dexterous in vivo robot platform successfully demonstrated the feasibility of performing a NOTES cholecystectomy from essentially a laparoscopic platform. The two-configuration design of the robot enabled sufficient flexibility for transgastric insertion while providing a stable platform for visualization and tissue manipulation. The placement of the cameras between the two robot arms improved triangulation compared with a flexible endoscopy platform. Furthermore, the robot design allowed the application of sufficient off-axis forces for tissue retraction and dissection. The addition of an ultrabright LED to the robot body in the third animal study greatly improved visualization of the surgical environment.

Although these studies successfully demonstrated the feasibility of performing an in vivo robot-assisted NOTES cholecystectomy, problems were encountered. The second study was converted to an open procedure after dissection of the cystic duct due to insufficient magnetic coupling for attaching the robot to the interior abdominal wall. The dissection of the gallbladder from its hepatic attachments was performed with the robot supported externally. The third study demonstrated improved visualization with sufficient magnetic coupling, but ended prematurely due to mechanical failure of the shoulder joint. These issues have been addressed in continuing iterations of the robot design without limiting robot functionality.

Discussion

Studies demonstrating the feasibility of NOTES procedures have identified significant challenges associated with using a flexible endoscopy platform to perform NOTES procedures. These devices are designed to be used with procedures in which the surgical target is in line with the light source and camera. These are conditions different from what exists for procedures in the peritoneal cavity, creating challenges in image stability, triangulation, force application, and multitasking capabilities. For NOTES to be widely adopted as an alternative to laparoscopic surgery, these challenges must be addressed.

One potential approach for addressing the limitations of the flexible endoscopy platform is to use miniature in vivo robots. An in vivo robot can be advanced into the peritoneal cavity using the upper approach. Once fully inserted, the robot is no longer constrained by the entrance incision, allowing the platform to provide stable visualization and sufficient force application from multiple orientations and workspaces within the peritoneal cavity.

The three animal model procedures using a dexterous miniature robot described in this report together demonstrate the feasibility of using an in vivo robot platform for performing NOTES procedures in the peritoneal cavity. Continuing improvements to the robotic platform are being pursued including an additional degree of freedom at the shoulder joint to improve cholecystectomy dissection and reduced size to enable peroral insertion. Also, cooperative robots are being developed that provide additional capabilities, including gross tissue retraction, to provide functionality sufficient for performing a NOTES cholecystectomy using only in vivo robots.

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DRAFT: MODULAR WIRELESS WHEELED *IN VIVO* SURGICAL ROBOTS

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ABSTRACT

Minimally invasive abdominal surgery (laparoscopy) results in superior patient outcomes as measured by less painful recovery and an earlier return to functional health compared to conventional open surgery. However, the difficulty of manipulating traditional laparoscopic tools from outside the patient's body generally limits these benefits to patients undergoing procedures with relatively low complexity. The use of miniature *in vivo* robots that fit entirely inside the peritoneal cavity represents a novel approach to laparoscopic surgery. Our previous work has demonstrated that mobile and fixed-based *in vivo* robots can successfully operate within the abdominal cavity and provide surgical vision and task assistance. All of these robots used tethers for power and data transmission. This paper describes recent work focused on developing a modular wireless mobile platform that can be used for *in vivo* sensing and manipulation applications. The robot base can accommodate a variety of payloads. Details of the designs and results of *ex vivo* and *in vivo* tests of robots with biopsy grasper and physiological sensor payloads are presented. These types of self-contained surgical devices are much more transportable and much lower in cost than current robotic surgical assistants. These attributes could ultimately allow such devices to be carried and deployed by non-medical personnel at the site of an injury. A remotely located surgeon could then used these robots to provide critical first response medical intervention irrespective of the location of the patient.

Keywords - Surgical Robots, In Vivo, Laparoscopy, Modular, Wireless, Mobile, Sensors

INTRODUCTION

Conventional open surgical procedures are performed by on-site, highly trained medical teams that use large incisions to gain access to the operating site. It is widely accepted that the trauma inflicted while gaining access to the operating site often causes additional injury to the patient, resulting in more pain, longer recovery times, and increased morbidity [1, 2 and 3].

Minimally invasive surgery (MIS) reduces this collateral trauma by using tools inserted into the body through small incisions. Laparoscopy is MIS performed in the abdominal cavity with long, slender tools inserted through small tool ports (trocars) placed in the abdominal wall of the patient. Studies clearly show that laparoscopic procedures result in shorter hospital stays, less pain, faster return to the normal activities of daily living, and improved immunologic response [4, 5 and 6].

The overwhelming success of laparoscopy in relatively simple procedures (e.g. gallbladder removal) has not, however, been replicated in more complex procedures [1]. The principal reason for the limited application of laparoscopy to more complex procedures is that the small incisions used in MIS impose significant constraints on the surgeon that result in severe ergonomic limitations, reduced dexterity, and limited perception [3].

Surgical robotic systems have been developed that attempt to augment surgical dexterity and visual feedback using features such as articulating end effectors, tremor filtering, motion reversal correction, stereoscopic vision, and motion scaling [7, 8 and 9]. However, these systems are all implemented from outside the body and remain constrained to some degree by the small incisions. Moreover, they offer limited reduction in patient trauma compared to conventional laparoscopy because multiple access ports are still required to perform surgery.

An alternative approach for robotic surgical systems involves placing miniature robotic assistants entirely inside the abdominal cavity of the patient. By placing robotic tools inside the peritoneal cavity, near the surgical site, critical issues related to ergonomic limitations, reduced dexterity, and limited perception are alleviated. The robots being analyzed in this paper are small and cylindrical in shape for easy introduction into the abdominal cavity through a laparoscopic port or natural orifice. The mobile platform enables the surgeon to arbitrarily relocate the robots within the abdominal cavity. Multiple robots that can be used for task assistance and visual feedback can be introduced using only one laparoscopic port, thereby making single-port surgical procedures possible.

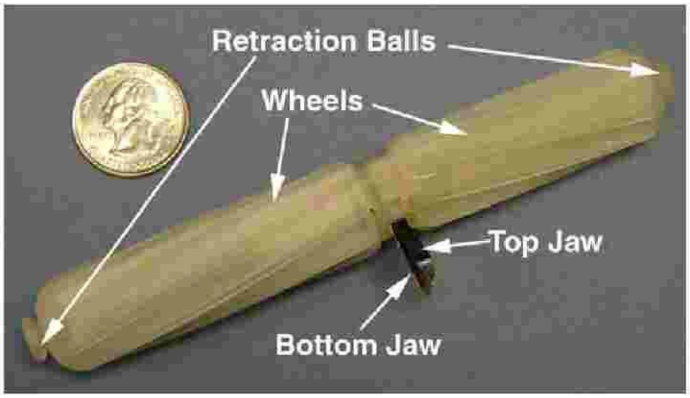

Figure 1. Modular robot platform with biopsy grasper.

This paper describes design details and results of *ex vivo* and *in vivo* tests of modular wireless wheeled robots with biopsy grasper and physiological sensor payloads. A modular design approach facilitates rapid development of several different payload capabilities without altering the power and control portion of the mobile platform. Future payload options, such as an adjustable focus camera, are also discussed.

BACKGROUND

A. Robot-assisted MIS

The development of robotic surgical tools has helped to reduce some of the limitations and complications associated with traditional manual laparoscopy. The first robots designed to assist during minimally invasive abdominal surgery (e.g., LARS and AESOP) appeared in the mid 1990s [10, 11]. The most commonly used robot today is the da Vinci surgical system, which received FDA clearance for sale in July, 2000 and is made by Intuitive Surgical. It is currently the only system commercially available, although other systems such as AESOP are still used. The da Vinci is a tele-robotic system that is controlled by a surgeon at a console. It serves in a master-slave relationship with the surgeon, where robotic arms hold the camera and instruments. Advantages of such robots include reduction of tremor, additional articulations in surgical instruments, corrections for motion reversal, and motion scaling. However, these robots are situated outside the patient, and thus remain subject to the dexterity limitations imposed by the use of long tools inserted through small incisions. Most studies suggest that current externally-situated robotic systems offer little or no improvement over standard laparoscopic instruments in the performance of basic skills [12, 13].

Moreover, da Vinci is cumbersome and requires difficult tool changes [4, 14], significant set-up time and significant operational space [15]. The movement of the large external arms makes direct access to the patient difficult, and their motion must be limited to avoid internal and external collisions [7]. A limited range of motion for the robotic camera can still result in obstructed or incomplete visual feedback.

Current efforts are focused on developing next generation robots that improve mobility and sensing capability while reducing complexity and cost. The Medical Robotics Group at UC Berkeley has built and tested a prototype laparoscopic robot with force and tactile feedback for telesurgical applications [16, 17]. The Carnegie Mellon University Robotics Institute is developing intelligent microsurgical instruments to electronically cancel tremor in handheld surgical tools [18, 19]. Prototypes of new endoscopic tools with force and tactile feedback are being created at the Bio-Robotics Laboratory at the University of Washington [20].

Other work is focused on developing robots in which all or most of the device enters the body. The simplest such mechanisms have been maneuverable endoscopes for colonoscopy and laparoscopy [21, 22]. These devices possess actuators to rotate the endoscope tip after it enters the body. Other *in vivo* robots have been developed to explore hollow cavities (e.g., the colon or esophagus) with locomotion systems based on 'inch-worm' motion that use a series of grippers and extensors [23], rolling tracks [24], or rolling stents [25]. These devices apply radial pressure to the walls of the hollow cavities they explore, and thus can not operate in the open space of an insufflated abdomen.

Another approach relies on an untethered pill that is swallowed and passively passed through the gastrointestinal (GI) tract. One such commercially available device [26, 27] returns thousands of images as it naturally moves through the GI tract. However, because the device is passive it cannot be directed to image a particular location, and the precise locations of the images returned are unknown. Combined with the large number of images, the use of this device for diagnosis is difficult. Other similar devices are now available [28, 29]. Dario et al. have recently described an endoscopic pill with an active locomotion system that uses legs to push against the gastrointestinal walls [30, 31], and a clamping system that uses shape memory alloys [32]. This device is still in a conceptual development stage.

A proof-of-concept design of an *in vivo* stereoscopic imaging system has been described by Miller et al. [33]. Actual prototypes and *ex vivo* and *in vivo* tests have yet to be completed. Finally, the HeartLander robot employs a suction-based drive to move across the surface of the beating heart [34, 35]. Prototypes have demonstrated successful prehension, turning, locomotion, and dye injection in a porcine model.

B. In Vivo Laparoscopic Robots

Most of the *in vivo* robots described above require narrow cavities or natural processes for their mobility systems to function, and/or external connections for actuation, power, and tool control. The open environment of an insufflated abdomen during laparoscopic surgery is incompatible with many of these approaches.

The use of miniature *in vivo* robots that can be inserted through a small incision and fit entirely within the peritoneal cavity represents a novel approach to laparoscopic surgery. Our previous work has focused on developing a family of *in vivo* fixed-base and mobile robots, and demonstrating that they can successfully operate within the abdominal cavity. These robots have been used to enhance the ability of laparoscopic surgeons to visualize the surgical field [36, 37], and to obtain tissue samples during a single-port liver biopsy in a porcine model [38]. However, all of these robots relied on tethers for power and data transmission, and each robot was designed for a specific task.

These types of low-cost and easily transportable robotic devices could eventually become standard equipment carried and deployed by non-medical personnel at the site of an accident or injury. A remotely located medical team could then use these devices to deliver a rapid therapeutic response and continually monitor physiological parameters prior to and during transport without cumbersome external connections. This paper presents our current progress towards developing a wireless, modular *in vivo* robot that could be field-configurable for specific incidents to support remote first-response medical care.

MOBILE ROBOT DESIGN

The general design of the wireless mobile robotic platform builds upon our earlier work developing tethered *in vivo* mobile robots [38, 39 and 40]. It consists of a cylindrical inner housing, two wheels that slip over the housing, and a tail that can be collapsed into the wheel treads when the robot is inserted or retracted through a trocar. The wheels allow for forward, reverse and turning motions, and the tail prevents counter rotation of the robot body when the wheels are turning. Depending on the modular payload, the tail can be as simple as a stainless steel coiled spring. In the case of a biopsy grasper arm or other payload that protrudes perpendicularly from the robot body, the payload arm itself can be designed to provide the functions of a tail.

In the long term we expect fabrication costs for each robot to be a few hundred dollars. We also anticipate these to be single-use disposable devices to mitigate challenges of re-sterilization, component fatigue, and battery recharging.

A. Robot Base Design

The construction of the robot inner housing differs in several significant ways compared to previous efforts. The housing itself is modular, consisting of two halves with each half comprised of two clamshell-like pieces with a semi-circle profile. Stereolithography prototyping techniques are used to manufacture the housing components out of ultraviolet-cured PolyJet FC720 Clear 83D. The housings components are assembled using UV-cured adhesive and mechanical fasteners.

Each half of the inner housing has a specific purpose. One half of the body houses the power plant (i.e., battery), the master control microprocessor and radio frequency (RF) communication electronics, and a permanent magnet direct current wheel motor. The second half of the body also houses a wheel motor, but the majority of the volume is a dedicated payload space (e.g., biopsy, sensors, etc). This design approach provides for a common mobile platform that can be easily re-configured for a variety of task specific applications.

B. Wheel Design

Internal abdominal organs and surfaces are highly deformable and very slick, and the constitutive relations describing wheel-organ interactions are quite different compared to those of terrestrial terrains. We have previously explored the nature of wheel-tissue interactions through analytical modeling and empirical analysis of experimental results [39]. This work led to a general helical tread wheel design that has been shown to provide mobility across abdominal organs and surfaces without causing tissue damage [38]. Additional work using finite element analysis [40] has provided a better understanding of how changes in robot mass and wheel geometry affect robot mobility.

Based on these results, wheels were designed for the current application. These wheels are 20 mm in diameter with 9 helical grousers arranged in a corkscrew pattern. The grousers have a depth of 1.5 mm, a thickness of 1.75 mm, and are spaced at 7 mm intervals. The pitch angle is 10.6° so that a minimum of two grousers are in surface contact at all times to help ensure a smooth motion profile. The wheels are bored to accommodate the robot body housing and have an inner diameter of 16.25 mm with a wall thickness of 0.375 mm. The grouser treads provide additional mechanical support to the thin walls. The end of the wheel includes a small ball-like feature that facilitates handling of the robot by the surgical team using laparoscopic tools during insertion and retraction. The wheels are manufactured using the same stereolithography techniques and materials as used for the robot body housing.

Each wheel is actuated by a 6 mm diameter permanent magnet direct current (PMDC) motor with a 256:1 gear ratio manufactured by MicroMo. A spur gear on the motor shaft couples the motor to a spur gear and bearing assembly mounted on the end of each wheel. A schematic of the robot platform is shown in Figure 2.

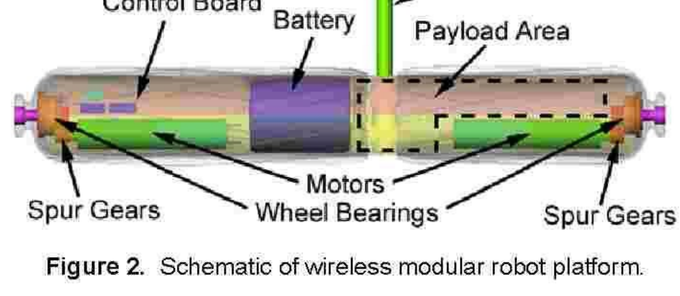

Figure 2. Schematic of wireless modular robot platform.

C. Electronics and Communications

The robot master control circuit board is shown in Figure 3. This is a custom designed double-sided surface mount printed circuit board (PCB) that incorporates an RF transceiver, a multi-channel integrated circuit (IC) that can drive both voltage-controlled and constant current-controlled actuators or other components (e.g., permanent magnet DC motors; voice coils), and a master microprocessor control unit (MCU).

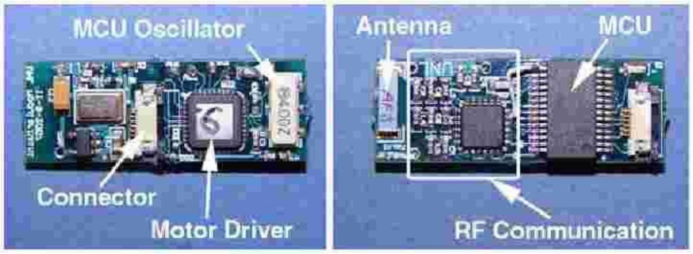

Figure 3. Top view (left) and bottom view (right) of master control circuit board for modular robot.

The communication unit is built around a Nordic nRF2401A 2.4 GHz ISM band single-chip radio transceiver. This low-power, fully-integrated transceiver is capable of error-checked data rates up to 1 Mbps in burst mode. Because there are 125 receive/transmit channels, multiple robots can be used simultaneously without interfering with one another. The transceiver is configured using a 3-wire serial interface to the control board MCU. A differential to single-ended matching network based on the Nordic nRF2401 reference design is used to accommodate a single-ended connection to a 50 Ohm chip antenna (LINX ANT-2.45-CHP).

A Toshiba TB6557FLG driver IC is used to provide up to six H-bridge (two constant current-controlled and four voltage-controlled) output drivers. This IC is also configured using a 3-wire serial interface to the MCU. Two of the voltage-controlled outputs are generally dedicated to controlling the PMDC wheel motors. A third voltage-controlled output is used in the biopsy robot to drive the grasper motor. Other types of actuators and components can be accommodated with the current design. For example, it is anticipated that the constant current-controlled outputs will be used in a future robot to control a voice coil actuator as part of an adjustable focus camera system. It is also likely that a light emitting diode (LED) lighting system can be controlled similarly.

The master MCU is a PIC16LF767. This low-power processor includes a 10-bit analog-to-digital converter with up to 11 input channels, three independent pulse width modulation modules, and extensive power management features that can minimize power requirements. In its current configuration, the processor operates at 4 Mhz, although a variety of lower or higher frequencies can be used. The MCU is responsible for configuring the various robot peripherals (e.g., transceiver, driver IC, and sensors), reading the sensor data, controlling actuators, transferring data to and from the communication module, and various other housekeeping tasks. The MCU control program is currently common across all robot variations. However, various application specific routines can be turned on or off to improve performance by using a MCU input pin to set internal flags. For example, because there is no need for the biopsy robot to execute code related to reading and transmitting sensor data, this portion of the code can be disabled without reprogramming the entire device.

All on-board power is provided by a single high power 125 mAh lithium organic cell battery (Tadiran TLM-1520HP). This battery has sufficient energy density to operate the robot for more than 1 hour with all motors running continuously. A stationary sensor robot will operate for more than 3 hours.

External control systems have also been developed to send control commands to the robot and process the *in vivo* data telemetry stream. These systems incorporate the same microprocessors and RF transceivers as the *in vivo* robots. Additional components are included as human interface devices (e.g., joysticks used to control robot wheel speed and direction; RS-232 data transfer to an external storage computer), and the microprocessor software is modified to reflect these differences.

PAYLOAD DESIGN

A. Biopsy Grasper and Actuator

Most surgical interventions require some ability to manipulate tissue. To demonstrate the feasibility of a wireless *in vivo* robot to provide surgical task assistance, a biopsy grasper and actuation mechanism payload was developed.

Traditional laparoscopic biopsy sampling tools typically consist of a grasper on the distal end of a long flexible tube, and a handle and lever system on the proximal end. A Teflon-coated wire that runs through the tube is affixed at one end to the handle lever, and at the opposite end to the grasper. Actuation of the handle causes the wire to translate relative to the tube and actuate the biopsy grasper. Laparoscopic biopsy grasper jaws do not overlap and completely sever tissue as do the jaws of many of the biopsy punches used in conventional surgery. Laparoscopic biopsies are, therefore, typically "grasp and tear" procedures that require a relatively large amount of force to tear the sample away from the organ. Because the miniature motors used to actuate the *in vivo* robots cannot directly generate sufficient forces to retrieve tissue samples, significant effort was applied towards developing an actuation mechanism with a large mechanical advantage. Additional attention was devoted towards designing the mechanism and biopsy grasper tool such that multiple tissue samples could be obtained. Another key aspect of the actuator mechanism design is that it can potentially be used with a variety of end-effectors in addition to a biopsy grasper (e.g., a clamp to hold tissue and/or control hemorrhaging).

Following a lengthy series of bench top tests, a promising general mechanism design was identified. A prototype is shown in Figure 4. The prototype biopsy grasper resembles a jaw. Unlike other laparoscopic biopsy forceps in which both jaws are hinged about a pivot point, only one jaw of the robotic grasper moves during sampling. The lower half of the grasper remains stationary and is profiled such that it provides a rigid and stable base against which the upper jaw can cut. The fixed bottom jaw is constructed from a hypodermic medical stainless steel tube and it forms the reservoir for storing multiple samples.

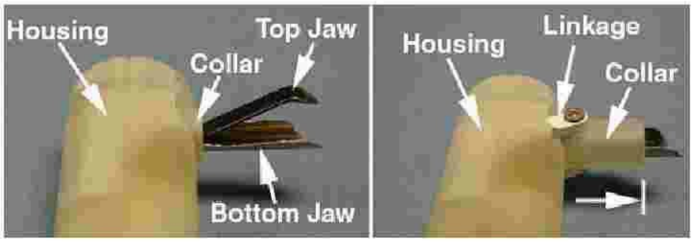

Figure 4. Biopsy mechanism actuation shown in open (left) and closed (right) positions.

The upper jaw is constructed out of a super-elastic shape-memory nickel titanium alloy (Nitinol) ribbon (Memry Corporation) 0.25 mm thick and 3 mm wide. It is profiled such that the grasper is normally open. A wide variety of profiles can be achieved by heat-treating the ribbon for approximately 10 min at 500 °C, followed by quenching in water. The edges of the ribbon are sharpened to a blade for cutting through tissue. The Nitinol ribbon is glued to a fixed nylon rod insert that fits inside the bottom jaw. The nylon rod is also glued to the bottom jaw, and anchors the biopsy grasper when the collar is actuated.

A tissue sample is obtained by using a PMDC motor to actuate a collar that slides over the grasper such that the upper jaw closes and overlaps the lower jaw. When implemented on a robot, the biopsy arm will be perpendicular to the robot body and actuator motor. Therefore, an actuation linkage inspired by our previous work [38] is used to transform the direction of translation of a lead nut driven by the motor to an axis inline with the movement of the collar. The limit of translation of the lead nut is such that the linkage approaches a mechanical singularity at the point of grasper closure, producing a large mechanical advantage.

1) Actuation Forces

Biopsy graspers based on variations of this preliminary design were constructed and incorporated into a bench top jig for more extensive testing.The principal goal was to investigate the effects of different grasper profiles and lengths on the forces required to actuate the mechanism, and the maximum forces that could actually be applied by the mechanism. The test jig includes a load cell that is used to measure the tensile force in the nylon supporting rod when the collar is actuated. Figure 5 shows the test jig with the motor, linkage, lead nut, collar, biopsy grasper and load cell. For these tests, the nylon rod extends out of the distal end of the bottom jaw stainless steel tube and is threaded into a Delrin connector attached to the load cell. The support brackets shown in the Figure are used to keep the nylon from bending during actuation.

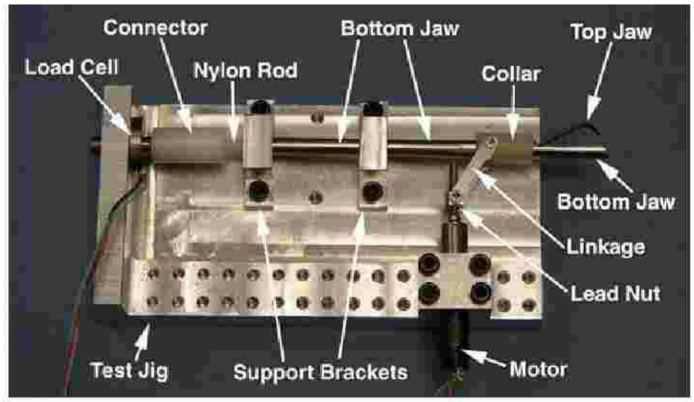

Figure 5. Jig for force testing.

Measurements of actuation forces were made for graspers with a wide range of jaw lengths, opening angles, and jaw profiles. Required actuation forces were determined by using the motor and lead screw linkage to slide the grasper collar over the jaws until closed. For each actuation, the required force was recorded starting with the grasper completely open and continuing until the grasper was closed. Maximum actuation forces were determined by recording the forces that could be applied with the collar held fixed at various positions corresponding to different times during actuation process. Each complete test consisted of 50 actuations of the biopsy grasper. Load cell data were recorded during each actuation at a rate of 20 Hz.

The results of these tests were used to develop a final candidate grasper design. This grasper is approximately 12 mm long, has an opening angle of 25° and a cutting tip with a length of 4 mm profiled with a closing angle of approximately 40°. Mean results from the required force test for this grasper are shown in Figure 6. The error bars indicate the standard deviation in the measured forces at intervals of approximately 1.8 seconds. The maximum required actuation force of 2.83 N is at the very start of the motion of the collar due to the need to overcome static friction and to begin flexing the top jaw of the grasper. The force decreases with time as the contact point between the collar and the top jaw moves farther away from the anchor point. The test results indicate that a maximum force of approximately 3 N is required to close the biopsy grasper.

Following each required actuation force test, the jig was reconfigured to measure the maximum force that could be applied using a motor to actuate the collar. The motor was operated using a power supply with the same voltage (4 V) as the battery used to power the robot motors. The maximum stall current was approximately 400 mA, well below the peak current (2.5 A) that can be supplied by the battery. At the start of actuation, with the biopsy grasper fully open, the maximum applied force is 7.3 N. This is greater than twice the force required to begin to close the jaw. The angle between the collar and the lead screw linkage decreases as the collar slides along the biopsy arm, increasing the applied force. A maximum applied force of approximately 13.2 N is attained at the translation limit of the collar at which point the grasper is completely closed. This is approximately 5 times the required force.

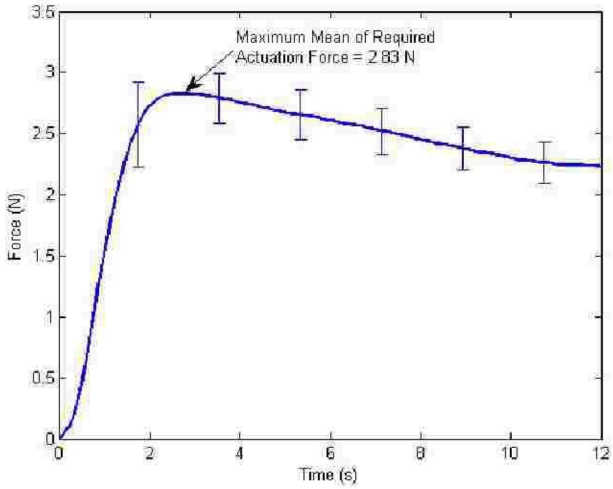

Figure 6. Required actuation forces for the biopsy grasper.

2) Ex Vivo Results

Ex vivo tests were conducted to characterize the ability of the grasper to obtain tissue samples. The biopsy grasper and actuation mechanism were placed inside the payload area of the modular robot platform. The motor and lead screw linkage were then used to actuate the grasper, as in the previous tests. However, during this experiment the grasper was positioned such that it would bite into fresh bovine liver, used as a proxy for porcine hepatic tissue, as it closed (Figure 7 left).

This sampling test was repeated multiple times. As illustrated in Figure 7 (right), multiple samples could be collected in the reservoir formed by the stationary bottom jaw of the biopsy grasper. In each test, the overlapping jaws completely or nearly completely severed the sample from the remaining tissue mass. In the cases of incomplete severing, the degree to which the samples were cut from the main body of tissue greatly exceeded that which is typically achieved with standard laparoscopic biopsy forceps. Previous analysis [40] indicates that the mobile robot platform has sufficient traction to provide the very small additional force that will be needed to pull a partially severed sample away from the tissue.

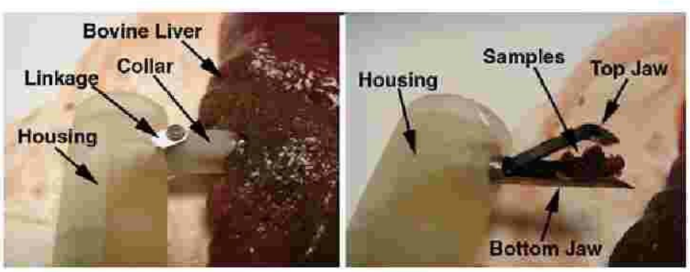

Figure 7. *Ex vivo* tissue sample collection (left) and multiple tissue samples shown in biopsy grasper after sampling (right).

3) In Vivo Design Considerations

The bench top and *ex vivo* tests and results discussed in the previous Sections identified and characterized the general mechanical and geometric parameters of a robotic biopsy grasper mechanism. Additional refinements, however, are required to incorporate the proposed mechanism within the mobile platform for *in vivo* applications. These refinements are shown in a schematic of the *in vivo* biopsy grasper arm in Figure 8. When fully implemented, the grasper will be affixed to the distal end of an arm that is typically perpendicular to the body of the surgical robot. The overall length of the robot body diameter plus grasper arm is greater than the diameter of most laparoscopic trocars. To allow the robot and grasper to be inserted and retracted through a trocar, the collar is split into two pieces and the anchoring mechanism is modified. These components are then connected together with a unique support mechanism that provides rigidity during sampling and the ability to flex the grasper arm 90° for insertion and retraction.

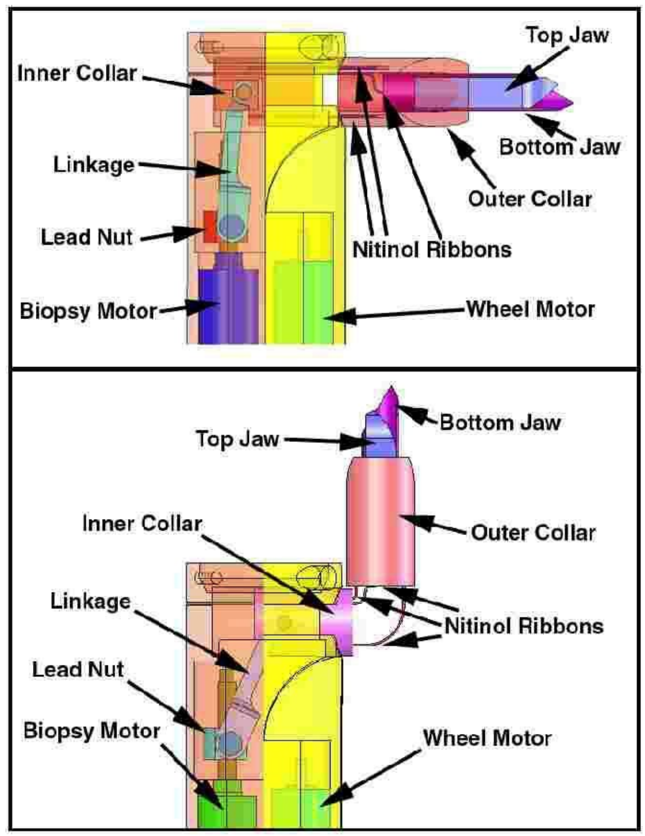

Figure 8. Schematic of the *in vivo* biopsy grasper in the normal (top) and flexed insertion configurations (bottom).

The two collar pieces are connected to one another by two 0.12 mm thick Nitinol ribbons that are anchored to the collar walls. A third Nitinol ribbon, connected to the biopsy grasper on one end and the robot body on the other, anchors the grasper when the collars are actuated. This ribbon is profiled for clearance around the lead screw linkage. These thin ribbons can be easily flexed and will spring back straight without kinking, physical deformation or memory effects. During insertion, the grasper arm can be flexed 90°. Once through the trocar, the ribbons return the grasper back to its normal orientation.

The only forces applied to the grasper arm during actuation are along the axial direction of the arm. Furthermore, organs and tissue within the peritoneal cavity do not have sufficient rigidity to flex the Nitinol ribbons as the robot maneuvers to various sampling sites. Consequently, the grasper arm will remain perpendicular to the robot body during sampling and robot navigation. During retraction, the grasper arm will again flex 90° as it comes into contact with edge of the trocar.

Other refinements were made to the linkage and the inner half of the collar. Specifically, the linkage is pinned to the inner surface of the collar, and the combined length of the inner and outer collar is such that it is longer than the stroke length of the lead screw. This ensures that the outside surface of either the inner or outer collar is always in contact with the opening in the robot housing so as to minimize fluid infiltration while the robot is in the *in vivo* environment.

B. Sensing

During laparoscopic surgery the abdominal cavity is insufflated with CO_2 to provide maneuvering space for tools and instruments. The temperature, pressure, and (sometimes) the humidity of this gas are monitored only externally to the body, and local conditions can vary dramatically. It is important for patient health and well-being during surgery that stable conditions are maintained. Without local measurements of these parameters, the actual conditions can only be estimated.

A modular wireless mobile robot platform equipped with a physiological sensor payload is shown in Figure 9. This custom designed PCB is currently configured to monitor the temperature (T), pressure (P), and relative humidity (RH) within the abdominal cavity. The module also includes additional electrical components and circuitry for power conditioning, power management, etc. This module is designed such that it can be used unchanged in a variety of applications, and it requires only connections for power and data communication.

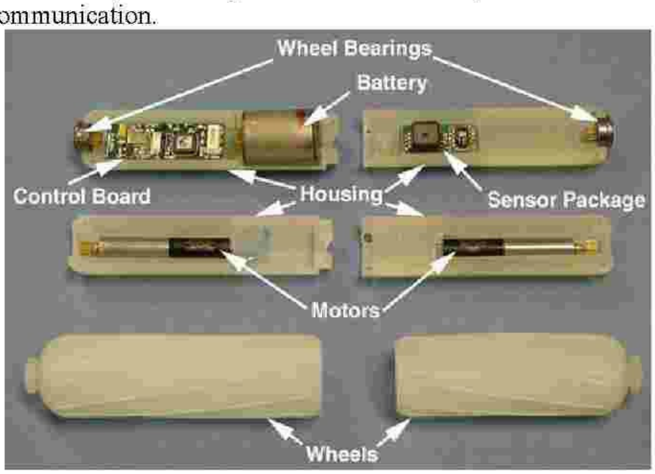

Figure 9. Exploded view of modular robot with sensor payload.

Temperature and relative humidity are currently measured using a single chip sensor module (Sensirion SHT15). This chip provides a calibrated digital output for both T and RH via an on-board 14 bit analog to digital converter. The data are transferred to the master MCU via a 2-wire serial interface.

Pressure is monitored using a Freescale Semiconductor absolute pressure sensor (MPXH6300A). This sensor has a full range of 300 kPA, and a sensitivity of 16.2 mV/kPA. A regulated charge pump (Microchip MCP1252) is used to boost the 3.3 V supplied by the master control board to the 5 V required by this sensor. Integrated on-chip conditioning networks provide a high output, temperature compensated signal. This signal is measured by the master MCU using its analog to digital converter.

This platform has been used to demonstrate the feasibility of *in vivo* sensory feedback. However, a variety of other sensors (e.g., pH, glucose level) can also be accommodated. For example, acidity levels (pH) within the peritoneal cavity can alert the surgeon to problems that can be harmful to the patient. For instance, a small tear or cut in the bowel may occur during surgery. While such perforations can be difficult to detect visually, significant related changes in acidity levels could be used as a marker to help avoid surgical complications.

IN VIVO RESULTS

A. Mobility

The ability of a wireless robotic platform to maneuver within the abdominal environment was demonstrated *in vivo* in a porcine model. The robot, equipped with a sensory payload, successfully navigated the entire abdominal cavity while providing physiological sensor feedback to a surgeon. The robot operated without any physical connections for power or bi-directional data telemetry. The robot was able to traverse all of the abdominal organs (e.g., liver, spleen, and bowel) without causing any visible tissue damage. Video recorded through a laparoscope was used to reconstruct the path traversed by the robot, a portion of which is illustrated in Figure 10. After exploring the abdominal cavity, the robot was parked where it continued to monitor temperature, pressure and relative humidity during the completion of other unrelated tests.

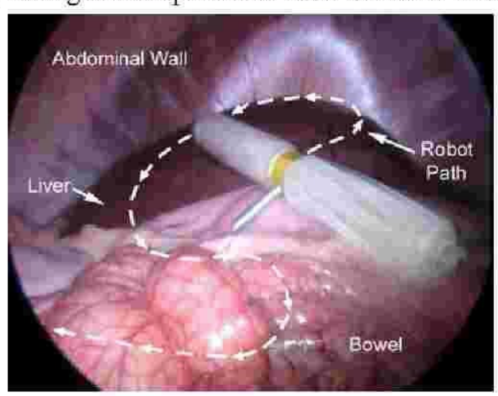

Figure 10. *In vivo* path traced by robot during porcine testing

B. *Telemetry and Sensing*

The telemetry and sensor platforms have been used in a series of *in vivo* tests in a porcine model to evaluate overall system performance. The reliability of the telemetry system was first independently examined [41]. A master control circuit board (without the driver IC) and battery were mounted in a protective silicon tube and placed into an insufflated porcine abdominal cavity. A similar *ex vivo* transceiver board located approximately 5 m from the operating table was used to send commands to the *in vivo* transceiver. The *in vivo* device was programmed to relay the received commands to a second *ex vivo* receiver. The data arriving at the *ex vivo* receiver were recorded to monitor the reliability of transmitted commands that made it to and from the peritoneal cavity.

Successful transmission is defined as a packet completing an entire loop of communication to and from the *in vivo* transceiver. Approximately 92% of all packets were successfully received *in vivo* for the duration of this test. Although the communication code has not yet been optimized, the performance of the system in its current configuration is sufficient to ensure the design goal of 10 Hz communication rates to and from the robot.

In a later test, a complete sensor module was integrated into the modular mobile robotic platform and the ability to monitor *in vivo* physiological parameters was evaluated. Figure 11 shows a typical plot of T, P, and RH variations within the cavity. This telemetry was monitored and recorded at a workstation located approximately 5 m from the operating table.

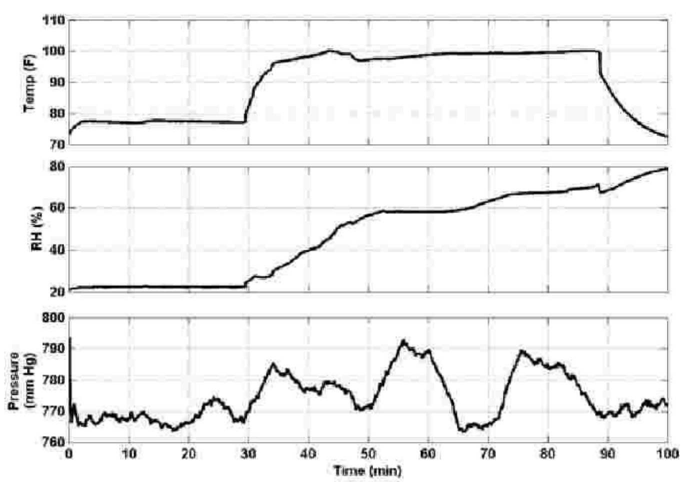

Figure 11. Sensory data from *in vivo* testing.

The data clearly track significant events during the test. The temperature, initially indicating room temperature, shows a rapid rise upon insertion into the abdominal cavity. The pressure and relative humidity data also show increases corresponding to the conditions within the insufflated cavity. The insufflation pressure was cycled several times during the course of the test, and those fluctuations are also apparent in the recorded data stream. After approximately 88 minutes, the robot was removed from the abdominal cavity, and the temperature and pressure return to *ex vivo* conditions. The relative humidity, however, continues to increase. A small amount of fluid was later found trapped within the body of the robot, which explains the high *ex vivo* humidity reading.

CONCLUSIONS

A modular wireless wheeled robot platform was designed that can accommodate various payload options to provide *in vivo* surgical assistance. The robot body consists of two distinct halves. One half is dedicated to the power plant and master control electronics that are common to all robot variations. The second half of the robot has a dedicated payload bay that can hold a variety of sensing and/or mechanical components. This design approach provides for a common mobile platform that can be easily re-configured for a variety of task specific applications.

A biopsy grasper and actuation mechanism payload was developed and tested *ex vivo* to explore its ability to provide surgical task assistance. The design includes overlapping grasper jaws that were shown to be highly effective at obtaining multiple tissue samples. The actuator mechanism and linkage are capable of providing 2-5 times the force required to close the jaws. A support and anchor mechanism using Nitinol ribbon cables provides rigidity during sampling and the ability to flex the grasper arm 90° during insertion and extraction through a laparoscopic trocar.

A physiological sensing payload was also implemented as a payload option to monitor temperature, pressure and relative humidity levels within the abdominal cavity during surgery. This module was incorporated into a complete wireless robotic platform and tested *in vivo* in a porcine model. The ability to control and communicate with the robot without requiring any physical connections for power or bi-directional data telemetry was demonstrated. The robot was able to navigate throughout the entire abdominal cavity without causing tissue damage. The reliability of the wireless transmission link and the ability of the sensor payload to track *in vivo* environmental conditions were also verified.

DISCUSSION AND FUTURE WORK

Taking a modular approach towards robot and payload design has helped speed the development and implementation of various payload options without requiring wholesale redesign of the entire robotic system. Current work is focused on *in vivo* testing of the biopsy grasper mechanism, and implementing a payload to provide a wireless vision system with adjustable focus capability. Future work includes developing a variety of additional payload options. One goal is to integrate a sensor payload and a grasping manipulator onto a single wireless mobile platform that could be used for targeted therapeutic diagnoses and interventions.

Another goal of this work is to demonstrate that a modular approach towards *in vivo* robot design can reduce development time and facilitate conversions between different payload options. This could improve the feasibility of ultimately providing emergency medical personnel in remote areas with the ability to deploy a cooperative team of robots with a variety of sensors and manipulators. Such wireless *in vivo* robotic surgical assistants could allow a surgeon to become a remote first responder irrespective of the location of the patient.

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A Modular Wireless *In Vivo* Surgical Robot with Multiple Surgical Applications

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Abstract. The use of miniature *in vivo* robots that fit entirely inside the peritoneal cavity represents a novel approach to laparoscopic surgery. Previous work demonstrates that both mobile and fixed-based robots can successfully operate inside the abdominal cavity. A modular wireless mobile platform has also been developed to provide surgical vision and task assistance. This paper presents an overview of recent test results of several possible surgical applications that can be accommodated by this modular platform. Applications such as a biopsy grasper, stapler and clamp, video camera, and physiological sensors have been integrated into the wireless platform and tested *in vivo* in a porcine model. The modular platform facilitates rapid development and conversion from one type of surgical task assistance to another. These self-contained surgical devices are much more transportable and much lower in cost than current robotic surgical assistants. These devices could ultimately be carried and deployed by non-medical personnel at the site of an injury. A remotely located surgeon could use these robots to provide critical first response medical intervention.

Keywords. Surgical Robots, Wheeled Mobility, *In Vivo*, Laparoscopy, Modular

Introduction

Conventional surgical procedures are performed by highly-trained medical teams that operate on-site through large incisions. Recent advances in minimally invasive surgical techniques reduce patient trauma [1], and telemedicine improves medical services to isolated patients [2]. Pioneering work by DARPA [3] to combine these techniques led to the development of the da Vinci Surgical System. However, current surgical robots are large, complex, expensive, and require multiple laparoscopic ports. Therefore, these systems are limited to a specific variety of tasks and locations in which those tasks can be performed.

An alternative approach is to place miniature robots entirely within the abdominal cavity, creating the possibility of single-port laparoscopic surgeries. *In vivo* fixed-based and mobile robots have been developed to provide surgical task assistance [4-5]. One specific example of task assistance is the use of a mobile biopsy camera robot to obtain a sample of hepatic tissue in a porcine model [6]. All of these robots relied on tethers for power and data transmission, complicating their use and limiting the potential for deployment in both traditional and remote environments. To improve these capabilities and facilitate the ability of remotely located medical teams to provide rapid therapeutic responses, a modular wireless wheeled *in vivo* surgical robotic platform was developed and tested in recent work [7]. The wireless robot shown in Figure 1 successfully navigated the abdominal cavity for approximately 3 hours while it transmitted temperature, pressure and relative humidity readings from inside the peritoneal cavity.

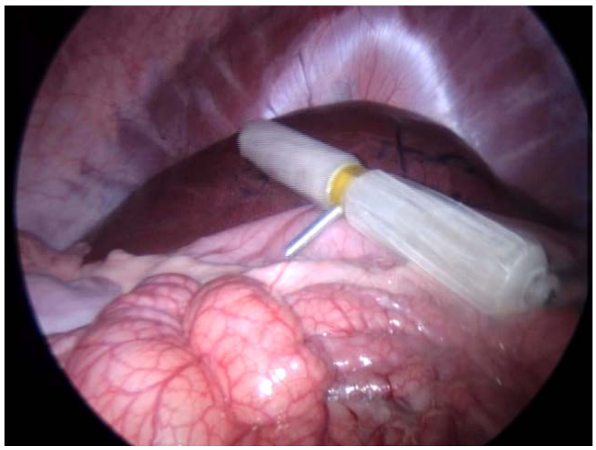

Figure 1. Wireless modular robot with sensory feedback payload.

1. Payload Variations for the Modular Platform

1.1. Biopsy Grasper

The biopsy grasper used in our previous work [6] was based on traditional laparoscopic biopsy graspers, which do not overlap when closing. As a result, laparoscopic biopsies typically consist of a "grasp and tear" technique. The motors used to actuate our *in vivo* end effectors can not directly produce the forces needed for this approach. Consequently, a new biopsy grasper was redesigned that maximizes the ability to sever tissue within the constraints imposed by the actuator motor. Force tests presented in previous work [8] were used to guide this redesign effort.

The newly designed biopsy grasper has a bottom jaw that is fixed during actuation to increase the mechanical advantage and create a stable and rigid base to cut against. Both jaws are fitted with sharpened tissue cutters constructed from titanium-nitrate-coated stainless steel. These blades tightly overlap so that the tissue sample is severed during actuation, reducing the force needed to extract the biopsy sample. A successful *in vivo* biopsy was performed using this modular platform. The sample was held in the reservoir formed by the bottom jaw until the robot was removed from the abdominal cavity, as seen in Figure 2.

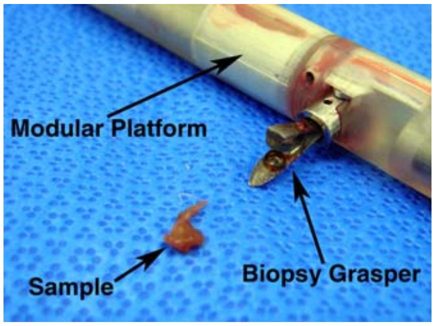

Figure 2. Biopsy grasper with liver tissue sample.

1.2. Stapling and Clamping

A similar type of grasper arm was then developed that could be used to staple blood vessels and manipulate tissue. During *in vivo* testing, this robot was used to staple a mesentery artery, shown in Figure 3. Inserts were fixed to the jaws of the grasper and profiled to hold a standard laparoscopic staple tightly in place while the robot maneuvers. Once the staple was delivered, the same grasper was used to manipulate the liver and other abdominal organs. The robot was able to tightly grip and position the liver in a desired orientation. The modular robotic platform allows the stapling grasper to be exchanged with the biopsy grasper in a matter of minutes. This type of quick exchange between payloads is feasible for any end effectors that would use a similar type of actuation.

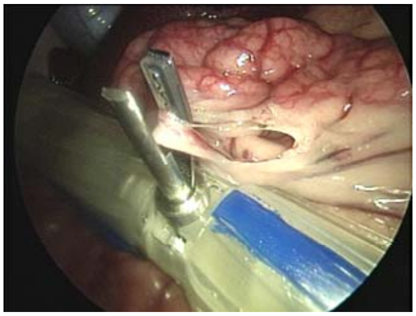

Figure 3. Stapling grasper positioned over a blood vessel.

1.3. Ceiling Pan/Tilt (CPT) Camera

Another payload option developed was a video camera board equipped with a color imager and LEDs to provide lighting. For this application the wheels of the mobile platform were replaced with a single outer housing. Magnets were embedded in the outer housing so that the robot could be magnetically attached to the inside of the abdominal wall. A magnetic handle on the outside of the abdominal wall is used to pan the camera. The motor in the modular half of the robot is used to control the tilt angle of the camera by rotating the entire modular platform about its long axis relative to the fixed outer housing.

2. Cooperative *In Vivo* Robots

The modular design facilitates rapid development of robots for different surgical tasks without a complete redesign of the robot. Incorporating the use of rapid prototyping manufacturing processes and ultraviolet-cured glue has allowed multiple prototypes to be developed simultaneously in an assembly-line style. End effectors, such as the biopsy grasper and stapling grasper are developed similarly. Consequently, a greater number of robot prototypes were developed during the past year than in any other previous year of development at our research facility. The increased number of prototypes allowed for more frequent testing of devices, and allowed researchers to design, build and test different robots in tandem.

Multiple robot platforms can also be inserted into the abdominal cavity simultaneously as seen in Figure 4. Moreover, they can operate cooperatively or independently because no cumbersome external connections exist. During *in vivo* tests, at least two robotic platforms with various payloads were inserted into the abdominal cavity. For example, in one test, a CPT robot was inserted and used to monitor the biopsy robot during a liver biopsy. The navigation of a sensing robot was also monitored, shown in Figure 5, as it transmitted physiological parameters (temperature, pressure, relative humidity) during the biopsy. Although this type of cooperation is at a very basic level, it demonstrates the feasibility of using these platforms to work together in a more coordinated fashion inside the peritoneal cavity. For example, a clamping grasper robot might be used to help position an abdominal organ or other object while other robots perform a tissue biopsy.

Figure 4. Two robots controlled simultaneously inside the peritoneal cavity.

Figure 5. CPT robot (left) viewing the sensor robot (right) during *in vivo* testing.

3. Conclusions

A modular wireless robotic platform was developed to assist surgical procedures inside the peritoneal cavity. The platform was tested *in vivo* in a porcine model. These tests successfully demonstrated the ability to sample tissue, manipulate abdominal organs, clamp blood vessels, and to provide visual and physiological sensory feedback from mobile wireless platforms. The modular platform facilitates rapid development leading to an increase in prototype testing. Rapid payload conversion between many different surgical tasks is another advantage of the modular design. For example, different end-effectors can be quickly exchanged or inserted during an operation. The robust modular platform could collect and extract a biopsy sample. Then, minutes later, could be reinserted with a different grasper to clamp a blood vessel or manipulate an abdominal organ.

4. Future Work

Additional *in* vivo experiments to investigate applications of cooperative robots inside the abdominal cavity are in the planning stages. Likewise, new payload applications, such as a drug delivery system, will continue to be explored in our future work. The integration of multiple payloads into a single platform, such as a camera and grasper combination, will also be investigated. Improvements could also be made to the conversion between different payloads. Mechanical and electrical connectors between the modular and payload halves would reduce the time needed for payload changes. Using a "plug 'n' play" approach for payload conversion, one can imagine a first responder arriving at an injury site with the modular platform and a "tool belt" of payloads that could be used as required by the surgical task.

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